Final Report

Research and operations to trial innovative glass and photovoltaic technologies in protected cropping

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Project code:

VG16070

Project:

Research and operations to trial innovative glass and photovoltaic technologies in protected cropping (VG16070)

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Content

Summary

Experimental Strategy: Off the shelf, low emissivity Smart Glass film ULR-80 (SG), recommended by researchers from Swinburne University of Technology (SUT), was tested on three vegetable crops at the state-of-the-art glasshouse facility designed for research and commercial production of horticultural crops. The primary objective was to assess the effect of SG on plant growth, physiology, crop yield and quality in a controlled CO_2, temperature, nutrient and irrigation environment. We tested one cultivar (Tracey) in eggplant, two cultivars (Red (Gina) and Orange (O006614/Kathia)) in capsicum, and three cultivars (Skyphos-Butterhead, Rosaine -Red Cos and Claudius - Green Cos) of lettuce for the SG trials. The climbing vine vegetable fruit crops (eggplant and capsicum) were tested for two seasons and leafy vegetable crop (lettuce) was tested three times in a single season using the commercial practices of crop growth and management. We conducted SG trials in different light conditions to understand the impact of seasonal light variation under SG on plant growth and productivity. Eggplant trials were initiated in high light conditions (Summer and Spring) for both experiments, but capsicum trials were begun in low light (Autumn) in the first experiment and high light (Summer) in the second experiment. In the second capsicum experiment, we also tested the effect of elevated CO_2 (eCO_2) on the crop physiological and growth response to SG. In lettuce, the first experimental trial was conducted in high light conditions (Summer) and the other two experimental trials were conducted in moderate light conditions (early and late Autumn, respectively).

SG Reduced Light Penetration and Photosynthesis: SG blocked ultraviolet (UV) and higher light wavelengths, which contribute to heat generation, consequently reducing energy required for cooling, water and nutrient use (Chavan et al., 2020). However, SG also reduced intensity of the light in photosynthetically active radiation (PAR), particularly the red and far-red light wavelengths of the PAR spectrum. In addition, the light transmission under SG varied with light intensity leading to a higher reduction in PAR under high light conditions of summer relative to low light conditions of winter (Appendix 2- Figure 1). Limited light availability under SG reduced photosynthesis and photosynthetic capacity in a crop-specific manner. Reduced light intensity proportionately decreased photosynthetic rates in all crops, and lower photosynthesis led to a limited carbon supply for producing fruits. However, photosynthetic capacity was reduced in eggplant, but not in capsicum indicating that the eggplant leaves adapted to new light environment under SG (Chavan et al., 2020).

SG Reduced Yield, but not Quality, in a Crop-Dependent Manner: Fruit crops responded to reduced carbon availability by aborting some fruits leading to reductions in yield (~ -20%) (Chavan et al., 2020). However, the quality and nutritional value of the harvest was not significantly affected (Appendix 2- Figure 6, 7 and Table 2). The two capsicum cultivars responded differently to eCO_2. Elevated CO_2 stimulated yield of the Orange cultivar in control glass, but mitigated the negative impact of yield in SG in red cultivar. Preliminary data analysis shows that lettuce response to SG varied according to the cultivar and exhibited differences in pigmentation. Lettuce cultivars Butterhead and Green Cos exhibited a reduction in fresh biomass under SG (-10%), but yield was not affected in Red Cos. In conclusion, SG reduces yield in all crops (0 to -30%) depending on the light intensity, but to a greater degree during high light conditions, by reducing light available for photosynthesis, without significantly altering the postharvest quality.

SG Reduces Energy Use and Increases Water/Nutrient Use Efficiency: Detailed analysis of energy and nutrient use data collected during crop trials is underway. During eggplant trial, SG reduced chiller energy usage by 12% from mid-summer to mid-winter, and by 4% from early spring to early autumn. SG also decreased nutrient and water usage by over 20% in both experiments. Overall, SG reduced energy use and increased resource use efficiency during eggplant trial.

Future Perspectives: Comprehensive data analyses for physiological, biochemical and post-harvest response of eggplant, capsicum and lettuce experiments are still in progress. These data will provide information on SG impacts on plant biochemistry and carbon biosynthesis that contribute to fruit production. Data analyses are continuing on energy and nutrient/water use during the crop trials. The very large data sets generated during these experiments will take more time to fully analyze and develop for research publications. However, there are practical outcomes (seasonal variation in the response of the same crop to SG, suitable planting time to maximize crop yield and energy savings under SG, and genotypic differences to SG), that can be used and adopted by the industry.

Keywords

Light, photosynthesis, protected cropping, smart glass, greenhouse horticulture, light spectrum, eggplant, capsicum, lettuce, quality

Introduction

Climate change coupled with growing food demand and decreasing agricultural land (Roser & Ritchie, 2019), demands innovative technologies for crop production. Protected cropping involves cultivation of crops in controlled environment conditions and has the potential to address the key challenges of crop production including resource limitation, high-energy costs, and adverse effects of climate change (Rigby, 2019). Australia's greenhouse area is estimated around 1,300 ha with 17% of high-tech sector (around 14 individual industries with > 5 ha area) and 83% of low or medium tech sector (Smith, 2020), while the proportion of plastic greenhouses and glasshouses in the total Australian greenhouse area is around 80% and 20%, respectively (Rabobank 2018). Reviews by Chavan et al (2021), Maier et al (2021) (appendix 5) and Protected Cropping Australia (PCA) to assess market failures and constraints of the industry identified the lack of state-of-the-art facilities to test and evaluate new crop varieties and technologies to minimise energy costs and maximise production. Protected cropping is the fastest growing food-producing sector in Australia, valued at around $1.5 billion per annum at the farm gate in 2017. It is estimated that around 30% of all Australian farmers grow crops in some form of protected cropping system equivalent to 20% of total value of vegetable and flower production (Protected Cropping Australia, 2020). Estimated Australian greenhouse vegetable production area is highest for SA (580 ha), followed by NSW (500 ha) and VIC (200 ha), while QLD, WA and TAS account for < 50 ha (Smith, 2020).

High energy cost is a major issue for greenhouse operations, limiting the productivity and profitability of horticulture businesses across Australia. Innovations of energy-efficient design and renewable energy for greenhouses have shown huge potential to benefit the protected cropping industry. Recently, Swinburne University of Technology (SUT) has developed SG with a low thermal emissivity coating, which reduces heat gain during high radiation hot days, and blocks heat loss at night or on cold days (Lin et al., 2020). SG provides better heat insulation than normal glass and reduces energy costs for temperature control. In a computer simulation at SUT, SG significantly reduced the cost of heating and cooling by 40%, while slightly improving crop productivity. However, these simulations must be tested using real plants grown in a greenhouse facility. In addition, photovoltaic (PV) and solar thermal collector (STC) technology can be used to convert solar energy into electricity to reduce energy consumption in a greenhouse. These technologies should be tested on major vegetable crops in an advanced greenhouse facility on a ground- and rooftop-based approach.

The primary objective of this project was to determine the impact of SG on (1) light quality and quantity, (2) photosynthesis and carbon assimilation, and (3) leaf biochemistry, yield and nutritional quality of vegetable crops using a high-tech glasshouse facility. We also added energy sensors to each glasshouse bay to measure energy use (originally part of the SUT project, but further supplemented by WSU) and tracked water and nutrient use. We used standard management practices during greenhouse trials on commercial cultivars of eggplant, capsicum and lettuce to assess the efficacy of SG on reducing resource (energy, nutrient and water) use while minimising negative impacts on crop yield and quality.

We have delivered scientific evidence useful for levied vegetable crop growers regarding the potential use of innovative glass technologies to reduce energy, water and nutrient use, and the impact on yield and quality of climbing vine fruit crops and leafy vegetable crops.

Methodology

Facility description and glass specifications

The SG trials were conducted in the state-of-the-art glasshouse facility designed for research and commercial production of horticultural crops at Western Sydney University, NSW, Australia. The 1800 m^2 advanced glasshouse facility established in late 2017 is equipped with Priva software and hardware (Priva, The Netherlands) to monitor and control temperature, humidity, nutrients, CO_2, and irrigation. We used four 105-m^2 research compartments with precise environmental control of atmospheric CO_2, air temperature, RH, and hydroponic nutrient and water delivery. Each research compartment included six gutters, used to deliver nutrients and water, which support 120-150 plants.

Two research compartments were fitted with HD1AR diffuse glass (70% haze; control compartments) and two research compartments had HD1AR diffuse glass, but were also coated with ULR-80 window film (Solar Gard, Saint-Gobain Performance Plastics, Sydney, Australia). The SG film ULR-80 is a potentially suitable glazing material for greenhouse crop production. It has low thermal emissivity (0.87) which blocks the light that mainly contributes to heat, but transmits most of the wavelengths of light used by plants for growth in the PAR region. According to the manufacturer specifications, SG blocks ~88% light in the infrared (IR) and far-infrared (FIR) region between 780 nm and 2500 nm; and >99% light in the ultraviolet (UV) region between 300 and 400 nm. In addition, SG blocks 43% of total solar energy with 40% transmission, 54% absorption and 6% reflectance. The two control research compartments consist of roof glass (70% diffuse light) and wall glass (5% diffuse light).

Plant growth and management

We tested two climbing vine vegetable fruit crops (eggplant and capsicum) and a leafy vegetable (lettuce) crop under SG. While eggplant and capsicum were tested in replicate experiments, lettuce was tested in three consecutive monthly trials. For each experiment, six-week-old nursery-grown seedlings were transplanted in Rockwool slabs and transferred into two control hazed glass (Control) and two SG (Treatment) compartments. Each compartment had 6 gutters (length 10.8 m, width 25 cm, AIS Greenworks, Castle Hill, Sydney, NSW, AUS) with 10 Rockwool slabs (90 × 15 × 10 cm, Grodan, The Netherlands) per gutter. Two/three plants per slab were planted in the four middle gutters, and two/three plants per slab were planted in the two side gutters and served as buffer plants. All measurements were performed on the four middle gutters to avoid edge effects. Plants were grown at standard growth conditions under natural light and were provided non-limiting nutrients and water by the Priva computer-programmed fertigation (nutrients and water) system. In second experiment for capsicum crop trial (during second half), elevated CO_2 was used to grow plants in one SG and one control compartment. Two/three stems were selected to grow from each plant for climbing vine crops with weekly pruning and cutting according to commercial practices of crop production for vertical protected cultivation. Each stem was considered to be an individual plant for replication and all measurements were performed per stem.

Light environment measurements

Light quality and quantity were measured using a portable spectro-radiometer (PS300, Apogee Instruments, Inc., Logan, UT, USA) and a PAR sensor (LI-190SZ Quantum Sensor, LI-COR) at the roof level during both experimental trials. Except for the spectro-radiometer, all other sensors continually logged data providing output as 5-minute averages. Additional sensors including hobo pendant temp/light data logger (UA-002-08, Instrument Choice, Dry Creek, SA, AUS), PAR (LI-190R-SMV-50 Quantum Sensor, LI-COR), net radiometer (SN-500, Apogee Instruments) and diffuse light sensor (BF5 sunshine sensor, Delta T Devices) were deployed to measure detailed light profiles during the second experimental trial. Three Hobo pendant temp/light data loggers (at the base, middle and top positions of the canopy), five PAR sensors (at canopy level) and a net radiometer were installed in each chamber. The diffuse light sensors were installed in one control and one SG chamber.

Plant growth, productivity and quality

Plant growth parameters were measured periodically in all experimental trials. For fruit crops, height, buds, flowers, and developing fruits were measured periodically. For lettuce colour, SPAD (chlorophyll content) and Photosyn (photosynthetic parameters) measurements along with photos for other morphological traits were performed periodically. Leaf reflectance was measured for eggplant experiment-1 using an ASD spectro-radiometer (FieldSpec 4, Malvern Panalytical Ltd, Malvern, UK) with a spectral range of 350–2500 nm to determine spectral indices that are indicative of plant biochemical traits. While fruits were harvested weekly for eggplant and capsicum, lettuce was harvested once at the final maturity stage. The weight of individual fruit and the number of fruits per stem was recorded. Fruit quality parameters, including moisture (oven drying), pH, total soluble solids

(Brix), ash (furnace method), ascorbic acid, titratable acidity, nitrogen (DUMAS), fat (ANKOM) and elemental composition (XRF, AGVITA) content were performed.

Leaf gas exchange and *biochemical analysis*

Instantaneous steady-state leaf gas exchange measurements were performed using a portable, open-mode gas exchange system (LICOR). Measurements were performed at 1500 µmol m^{-2} s^{-1} PAR, 500 µl L^{-1} CO2 concentrations and 25ºC leaf temperature. The response of A_{sat} to light (Q) (A-Q curve) was measured at 25°C leaf temperature at 11 light levels (0, 25, 50, 100, 200, 300, 400, 500, 1000, 1500 and 2000 µmol m^{-2} s^{-1}). The response of A_{sat} to sub-stomatal CO_2 mole fraction (C_i) (A-C_i response curve) was measured in 8 steps of CO_2 concentrations (50, 100, 230, 330, 420, 650, 1200 and 1800 µl L^{-1}) at 25°C leaf temperature. Leaf samples were used for pigment analysis using high-performance liquid chromatography (HPLC) and gas chromatography coupled with mass spectrometry (GCMS).

Greenhouse cooling and heating mechanisms

The greenhouse PRIVA system managed all aspects of environmental control, including ventilation, cooling, heating, and fertigation. Plants were provided non-limiting fertigation managed by the PRIVA system. Aggregate data were sampled and logged by PRIVA at 5-minute intervals. The cooling system used chilled air coolers linked to external cooling towers via chilled water pipes. Compared to higher-efficiency greenhouse cooling technologies, such as fan-pad and mechanical coolers, energy consumption was higher and temperature control was comparatively superior. Thus, while the cooling system was unsuitable in approximation of an overall energy budget for commercial greenhouses, it was ideal for controlling research parameters and ensuring a good crop. The heating system used hot water pipes running through each room and connected to an external boiler. While all rooms were heated, only one room had a heating energy meter at the time of both experiments. Energy meters for both heating and cooling systems did not measure energy usage directly, unlike electricity meters. Instead, values in kWh were calculated based on a) differences between supply and return water temperatures, and b) pump speed. A single rooftop vent was installed in each room which alternated between being a lee-side or wind-side vent depending on wind direction. The percentage of vent opening was determined based on inside and outside humidity, CO_2 levels, and temperature. A fogging unit was also installed under the roof within each room, which in combination with vents, made relative humidity fairly stable at desired set-points. Outside climate parameters were measured from the greenhouse's own weather station. Thermal curtains were employed to control exposure to solar radiation, involving an approximate limitation of 50% radiation and 80% air exchange during. All rooms were subject to the same curtain strategy. During eggplant experiment 1, the curtain control scheme was largely automated by PRIVA, with curtains open between 8 AM and 3 PM prior to an hour-shift for daylight savings.

Statistics and data analysis

Data analyses and plotting were performed using R computer software (R Core Team, 2020). The treatment effect was analysed using one-way analysis of variance (ANOVA). The linear model involved testing each parameter at two treatment conditions (SG and control glass) using measurements from two SG and two control glass rooms. Replication was as follows: n = 10 refers to 10 plants/stems per treatment or 5 plants/stems from each chamber. The homogeneity of variance was tested using Levene's test from the car package. The parameters showing unequal variance (with less than 0.05 probability for Levene's test) were corrected using Welch's t-test for unequal variances using the oneway.test function in R. Other packages were also used, including (but not limited to) lubridate (for effective use of dates in plots), sciplot (for plotting) and doby (for calculating means and standard errors). Principle component analysis (PCA) was used to derive correlations and the significance levels for ANOVA were, $P > 0.05$=ns, $P < 0.05$ = *, $P < 0.01$= ** and $P < 0.001$ = ***.

Outputs

Stakeholder engagement through Industry Consultation Forums and Steering Committee:

We regularly interact with industry partners including Phil Jones (Greenworks), Edgar Lopez (Greenworks), Dion Potter (Syngenta), Nicky Mann (Family Fresh Farms), Troy Topp (Perfection Fresh), Tony Bundock (Genesis Horticultural Solutions), and Marcus Van Heijst (PRIVA) for consultation on crop, growth, management and greenhouse operation. Steering committee meeting with collaborators, growers and industry partners (Green Camel) was held on June 28, 2019. Research progress was discussed, and we received feedback for future research objectives. The meeting involved overview talks titled “Protected Cropping: Use of Smart Glass to reduce energy cost in future climates” by Prof David Tissue and “Progress and opportunities for renewable energy applications for greenhouse” by Prof Baohua Jia, followed by presentations by Western Sydney University (WSU) and Swinburn University of Technology (SUT) students and postdoctoral research fellows. Industry participants Nicky Mann (Chair, Protected Cropping Australia) and Levi Nupponen (MD Agrology Pty Limited) provided useful insights on the industry objectives and disseminating the research outcomes to growers.

Develop Recommendations and Guidelines for growers: Based on three crop trials (two fruit crops and a leafy vegetable crop) under SG and experiments for growth parameter optimisation, we were able to develop guidelines and recommendations on overall growth, morphology and general yield for these horticultural crops under SG. Greater mechanistic explanations for crop response, and molecular changes in fruit quality that could be used to develop nutrient-enriched fruits and vegetables, will be available following completion of lab work. The use of new light-shifting films developed by a Sydney-based start-up company (LLEAF) in the Future Food Systems CRC, was inspired by this SG project and expected to contribute more recommendations for growers.

Milestone status reports: Six-monthly milestone status reports detailing the progress of the project were successfully submitted on time periodically over the project timeline. The milestone status reports successfully updated industry about the crop trial progress and provided justification to select crops for trials under SG.

Final Report: A report is being submitted at the final report due date, but we will update it with more information following in-depth analyses. We have completed three crop trials under SG that included seven experiments, which will require more time to complete the lab work, data analysis and writing. We will be able to provide a more detailed report with the overall results for the SG project after completing lab work.

Training and skill development: Students, casual personnel and post-doctoral research fellows were successfully trained while working on the SG project. The project also supported skill development of industry beneficiaries as part of LP18000 (Emerging Leaders in Protected Cropping). The project involves a Master’s student (Chelsea Maier), two PhD students and one post-doctoral research fellow (Sachin Chavan) continuously working on the project since inception. In addition, two post-doctoral research fellows (Yagiz Alagoz and Chenchen Zhao) were supported by a complementary grant (Australia-India fellowship), with no cost to HIA, for one year to contribute to fruit crop trials.

Research output:

Summary: We successfully completed three crop trials under novel Smart Glass (SG). The trial crops included two climbing vine fruit crops eggplant and capsicum, and a leafy vegetable crop lettuce. We used one cultivar (Tracey) for eggplant, two cultivars (Red (Gina) and Orange (O006614/Kathia)) for capsicum, and three cultivars (Skyphos-Butterhead, Rosaine -Red Cos and Claudius - Green Cos) for lettuce to test the SG impact on plant growth, photosynthesis, yield and quality. The overall summary describing the light environment, photosynthesis, yield and quality for the different vegetable crop trials under SG is shown in Table 1.

Climbing vine vegetable crop trial 1 (Eggplant) – SG significantly reduced yield: The first climbing vine vegetable fruit crop trial under Smart Glass (SG) was completed using eggplants (*Solanum melongena, cv*. Tracey eggplant grafted on tomato *cv*. Kaiser stems). Eggplants were grown for two experiments, which started under high light conditions of summer (Jan 2018) and spring (Sep 2018), respectively. SG blocked UV and light wavelengths > 700 nm contributing to heat generation, which consequently reduced energy required for cooling, water and nutrient use. SG also reduced intensity of the light in photosynthetically active radiation, which limited photosynthesis and altered xanthophyll composition. A high fruit abortion rate reduced yield possibly through source-sink regulation due to low carbon availability under light limited photosynthesis. However, SG did not affect overall fruit quality. We concluded that light limited photosynthesis might have altered the source (carbon) to sink (fruits) ratio causing reduction in fruit yield without any effect on nutritional quality. We reported detailed eggplant trial results in the journal *Food and Energy Security* (Chavan et al 2020, appendix 5) along with preliminary energy, water and nutrient analysis based on energy meters. However, energy use is a complex parameter for the advanced glasshouse facility, and we are working on a comprehensive energy analysis for all crop trials. More information about the energy analysis of eggplant trial is available in Appendix 1.

Climbing vine vegetable crop trial 2 (Capsicum) – SG reduced yield: The second climbing vine vegetable fruit crop trial was completed using capsicum (*Capsicum annum, cv* Gina-Red and O006614/Kathia- Orange). For capsicum trials, the first experiment started in low light (Autumn) and the second experiment started in high light (Summer), which created different light environments for the two experiments. The low light experiment did not indicate an impact of SG on yield, but the high light experiment in SG did reduce capsicum yield. The variable response of yield is associated with the seasonal variation in light transmission under SG and important for growers to consider when they determine the timing of planting the crops. SG did not significantly affect light saturated photosynthetic capacity in both capsicum cultivars, but photosynthetic rates of both capsicum cultivars were lower in SG due to the reduction in light. In the lower light experiment, stomatal responses of capsicum to SG were affected by light intensity more than spectral quality (Zhao et al., 2021, appendix 5). Detailed results for growth and yield response of capsicum to SG in the lower light and higher light experimental trials are available in Appendix 2.

In the second (higher light) capsicum experiment, we also exposed the plants to elevated CO_2 (eCO_2) to determine whether eCO_2 could increase photosynthesis to compensate for lower carbon gain in ambient CO_2 due to reduced light in SG. We found that eCO_2 stimulated photosynthesis, which compensated for yield loss in Red cultivar, but not in Orange cultivar.

Leafy vegetable (non-fruit) crop trial 3 (Lettuce) - SG alters pigmentation and moderately reduced yield: We tested lettuce (cv Skyphos-Butterhead, Rosaine -Red Cos and Claudius - Green Cos) to determine the effect of SG on a leafy crop. For lettuce, the first experimental trial was conducted in high light conditions (Summer) and the other two experimental trials were conducted in moderate light conditions (early and late Autumn, respectively). SG decreased light more in high light conditions than in moderate light conditions. SG decreased yield in the first two experiments, but not in experiment 3. SG significantly altered leaf color in all three-lettuce cultivars. Interestingly, SG significantly reduced photosynthetic capacity only in cultivar Green Cos (GC). We are still analyzing some of the lettuce data, but results for growth and yield response are available in Appendix 3.

Table 1: Summary of light and key vegetable crop parameters in response to Smart Glass (SG). NA – data not available or in analysis. NS – not statistically significant.

Crop	Exp No	Growing Season		Cultivar	Growth CO_2 (µl L^{-1})	% Change Under Smart Glass			
		Start	End			Mean Light (PAR)	Photosynthetic capacity (A_{sat})	Mean Yield (All plants)	Quality (Overall)
Eggplant	**1**	**Jan 2018** Summer	**Jul 2018** Winter	Tracey	500	NA	-12	-23	NS
	2	**Sep 2018**	**Feb 2019**	Tracey	500	-21	-18	-21	NS
Capsicum	**1**	**Apr 2019** Autumn	**Nov 2019** Summer	Gina-Red	500	-20	NS	NS	NS
				O006614-Orange			NS	NS	NS
	2 – 1st Half	**Jan 2020** Summer	**Jun 2020** Winter	Gina-Red	500	-19	NS	-18	NS
				Kathia-Orange			NS	-26	NS
	2 – 2nd Half	**Jun 2020** Winter	**Sep 2020** Spring	Gina-Red	500	-23	NS	NS	NS
					800		NS	NS	NS
				Kathia-Orange	500		NS	-24	NS
					800		NS	-26*	NS
Lettuce	**1**	**Nov** 2020 Summer	**Dec 2020** Summer	Skyphos-Butterhead	500	-19	NA	-11	NA
				Rosaine-Red Cos			NA	NS	NA
				Claudius-Green Cos			NA	-10	NA
	2	**Feb 2021** Summer	**Mar 2021** Autumn	Skyphos-Butterhead	500	-18	NS	-11	NA
				Rosaine-Red Cos			NS	NS	NA
				Claudius-Green Cos			-11	-15	NA
	3	**April** 2021 Autumn	**May 2021** Autumn	Skyphos-Butterhead	500	-15	NS	NS	NA
				Rosaine-Red Cos			NS	NS	NA
				Claudius-Green Cos			-10	NS	NA

* Elevated CO_2 stimulated Orange cultivar yield under control glass but not under Smart Glass.

Outcomes

Research experiments: The project has provided scientific evidence regarding the use of SG in commercially important vegetable fruit and leafy vegetable crop cultivars. We tested the impact of SG on two climbing vine fruit crops (eggplant and capsicum) and one leafy vegetable crop (lettuce) in replicate trials. Overall, SG reduced light (PAR) by 15-30% which reduced photosynthesis up to 18% and yield in eggplant (21-23%), capsicum (up to 27%), and lettuce (up to 15%). However, crop quality was not affected, and there were reductions in nutrient and water use. There were season specific differences in crop response; e.g., SG did not reduce yield in capsicum experiment 1 (started in low light) but significantly reduced yield in experiment 2 (started in high light). Overall, the reduction in yield in all crops does not warrant use of the SG in cropping systems. However, if the current SG was re-engineered to increase UV light and more Red light, and less high wavelength IR radiation (which contributes heat but not plant-based productivity), then SG might be attractive to growers. We have provided the information to make these changes, so it would be up to film producers to make these alterations.

We also conducted optimization experiments for environmental control during periods when crops were not in the glasshouse. Roof vent operation was tested under different scenarios to passively reduce heat at the roof level, which consequently reduces the requirement for cooling and energy costs. We also trialed different PRIVA control programs for temperature control and nutrient recipes to optimize energy and resource use. The growth environment data collected by the PRIVA system during crop trials provided insight into efficient energy use and environmental control.

Industry engagement: The project has the potential for significant outcome in innovation and collaboration in the protected cropping industry to promote broader economic development across Australia. For example, the SG project has inspired a collaboration between WSU and a new start-up company LLEAF, which is currently funded by CRC Future Food Systems to test their new film. In addition, the SG project has allowed strengthening of multiple internal collaborations to address diverse aspects of protected cropping research, such as biological (growth, productivity and yield), physical (material science to alter glass or film characteristics) and economic (cost/benefit ratio) aspects. The SG project provided an excellent foundation for further research on cover materials and optimization of glasshouse control to reduce energy use while maintaining crop productivity and quality.

Social benefits: The research outcomes also include social benefits. We host thousands of visitors from schools, universities, protected cropping industry and described our SG technology. The engagement and outreach program raised the awareness of sustainable food production in Australian society via this "energy neutral" greenhouse project (appendix 4). Eggplants, capsicums and lettuce were donated to the Foodbank. The promotion and engagement activities have resulted in a significant increase in student enrolments in the Bachelor of Sustainable Agriculture and Food Security in 2020. A/Prof Oula Ghannoum wrote a review article titled "The green shoots of recovery" highlighting the potential role of protected cropping industry in addressing the solutions for global food security and recovering from COVID-19 pandemic (https://www.openforum.com.au/the-green-shoots-of-recovery/). An article on the status of SG project was published in "*Vegenote*" (a vegetable and potato industry publication by AUSVEG, https://ausveg.com.au/app/uploads/2019/12/AUSVEG_Vegenotes_Summer-2019_75_F01v1.pdf). The SG project update was also featured as a cover image in the future makers magazine https://www.nature.com/articles/d42473-020-00069-0 (appendix 5). Professors Tissue and Chen, and other team members have been giving radio, magazine, and web-based interviews and talks about this project (appendix 6).

Training and skill development: One of the key outcomes of the project was training and skill development for the protected cropping sector. This project provided a research platform for highly innovative postgraduate projects in order to advance and secure Australia's future international standing in greenhouse horticulture. The project employed several casuals who were trained to work in commercial crop production setup, thereby increasing the number of skilled personnel for the protected cropping industry. In addition, the project also provided a very good platform for post-doctoral early career researchers and technical officers to learn and advance their knowledge in protected cropping.

The SG project provided advanced sensors and data loggers that characterize the environment in the research bays, and developed a sophisticated pipeline for data download, access and analysis, which are essential for protected cropping research at the National Vegetable Protected Cropping Research Center (NVPCC). The SG project at the NVPCC was successful at attracting students and people from different sections of society to potential careers in protected cropping and food sector research, ultimately promoting awareness of sustainable food production.

Monitoring and evaluation

The project has been overseen by Prof David Tissue and Prof Ian Anderson. Prof Tissue and Prof Anderson worked with the project team members to deliver reports as per HIA requirements for consideration to the Steering Committee. They monitored progress of the project and ensured that the deliverables were met on time and within the budget. To co-ordinate progress and communications, meetings were organized between project leads (WSU and SUT) along with student and postdoctoral researchers at both the locations (WSU and SUT). A communications strategy was also developed in collaboration with the communication officer and Management Committee. The project team implemented the process of bringing together ongoing monitoring activities and evaluation studies into one overarching system. The project team developed a Monitoring & Evaluation plan upon commencement of the project. Costs for developing an effective monitoring and evaluation plan was factored into SUT's project budget.

Project steering committee was formed for the duration of the project and consisted of representatives from WSU, SUT, HIA, and protected cropping industry. The role of the steering committee was to:

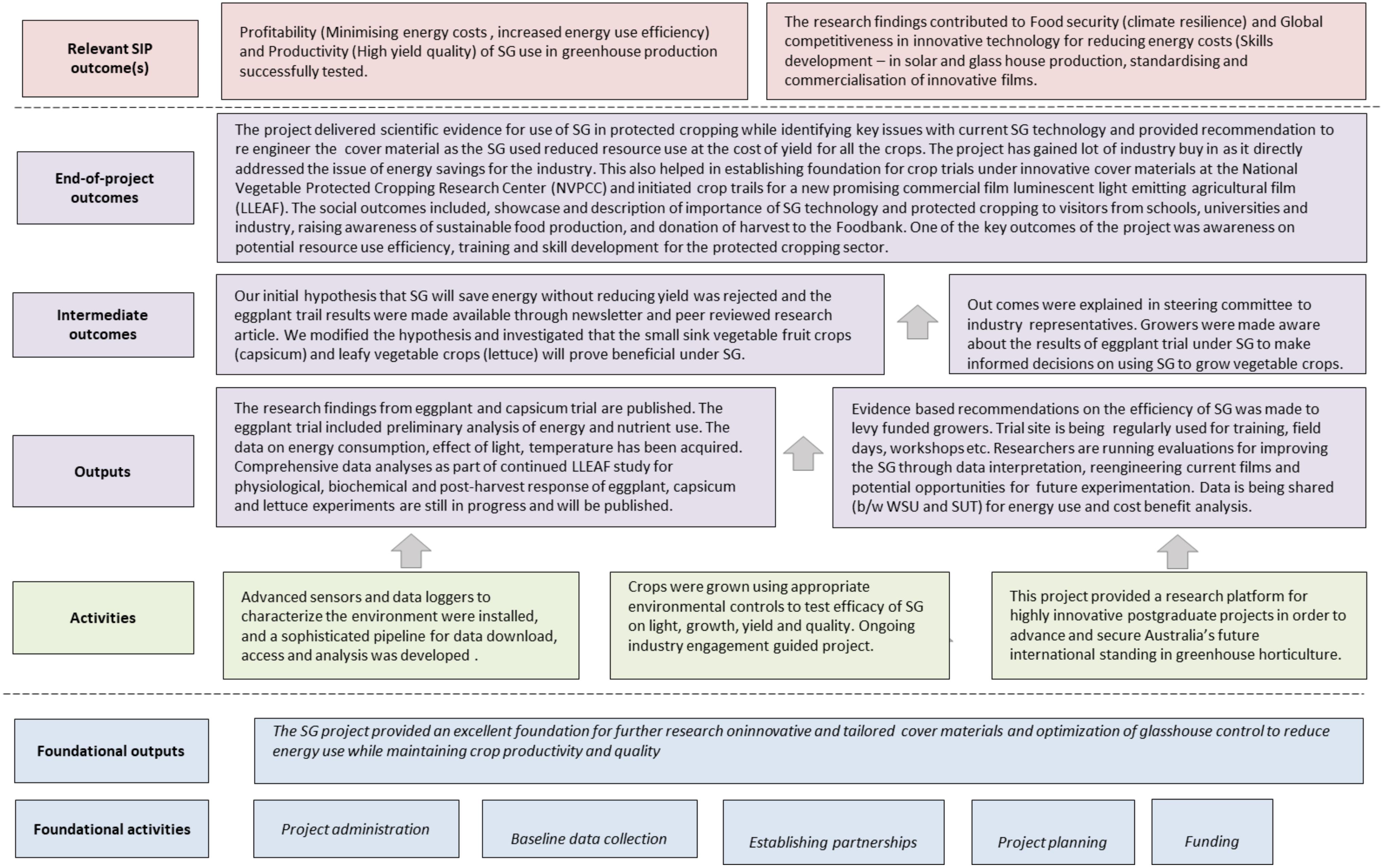
- review, comment and endorse project design, progress and outputs
- nominate and agree on the experimental plan, treatments and data collection
- approve the communication strategy and make announcements
- review recommendations from research and technical team on project design, progress and outputs
- review, approve and submit progress reports to the HIA.

The routine and systematic collection of data for management and/or evaluation purposes and systematic collection and analysis of data about processes, outputs and outcomes will allow the project team to make statements, judgements, claims and conclusions, which have the potential to impact on current and future decision-making. The project team will implement the process of bringing together ongoing monitoring activities and evaluation studies into one overarching system. The project team will develop a full Monitoring & Evaluation plan upon commencement of the project. Costs for developing an effective monitoring and evaluation plan is factored into SUT's project budget. Dr Nisha Rakhesh lead the development of monitoring and evaluation with HIA and SUT which is described in the following sections.

Research and operation trial innovation glass and photovoltaic technologies in protected cropping

- Program Logic

Figure 1 Program logic model for the Smart Glass project



Relevant SIP outcome(s)

Profitability (Minimising energy costs , increased energy use efficiency) and Productivity (High yield quality) of SG use in greenhouse production successfully tested.

The research findings contributed to Food security (climate resilience) and Global competitiveness in innovative technology for reducing energy costs (Skills development – in solar and glass house production, standardising and commercialisation of innovative films.

End-of-project outcomes

The project delivered scientific evidence for use of SG in protected cropping while identifying key issues with current SG technology and provided recommendation to re engineer the cover material as the SG used reduced resource use at the cost of yield for all the crops. The project has gained lot of industry buy in as it directly addressed the issue of energy savings for the industry. This also helped in establishing foundation for crop trials under innovative cover materials at the National Vegetable Protected Cropping Research Center (NVPCC) and initiated crop trails for a new promising commercial film luminescent light emitting agricultural film (LLEAF). The social outcomes included, showcase and description of importance of SG technology and protected cropping to visitors from schools, universities and industry, raising awareness of sustainable food production, and donation of harvest to the Foodbank. One of the key outcomes of the project was awareness on potential resource use efficiency, training and skill development for the protected cropping sector.

Intermediate outcomes

Our initial hypothesis that SG will save energy without reducing yield was rejected and the eggplant trail results were made available through newsletter and peer reviewed research article. We modified the hypothesis and investigated that the small sink vegetable fruit crops (capsicum) and leafy vegetable crops (lettuce) will prove beneficial under SG.

Out comes were explained in steering committee to industry representatives. Growers were made aware about the results of eggplant trial under SG to make informed decisions on using SG to grow vegetable crops.

Outputs

The research findings from eggplant and capsicum trial are published. The eggplant trial included preliminary analysis of energy and nutrient use. The data on energy consumption, effect of light, temperature has been acquired. Comprehensive data analyses as part of continued LLEAF study for physiological, biochemical and post-harvest response of eggplant, capsicum and lettuce experiments are still in progress and will be published.

Evidence based recommendations on the efficiency of SG was made to levy funded growers. Trial site is being regularly used for training, field days, workshops etc. Researchers are running evaluations for improving the SG through data interpretation, reengineering current films and potential opportunities for future experimentation. Data is being shared (b/w WSU and SUT) for energy use and cost benefit analysis.

Activities

Advanced sensors and data loggers to characterize the environment were installed, and a sophisticated pipeline for data download, access and analysis was developed .

Crops were grown using appropriate environmental controls to test efficacy of SG on light, growth, yield and quality. Ongoing industry engagement guided project.

This project provided a research platform for highly innovative postgraduate projects in order to advance and secure Australia's future international standing in greenhouse horticulture.

Foundational outputs

The SG project provided an excellent foundation for further research oninnovative and tailored cover materials and optimization of glasshouse control to reduce energy use while maintaining crop productivity and quality

Foundational activities

Project administration

Baseline data collection

Establishing partnerships

Project planning

Funding

Project M&E scope

a) Audience

Table 1: M&E audience and their information needs

Audience	Information need
Primary	
Project team (Primary) SUT Team- Prof. Baohua Jia, Dr Han Lin WSU Team- Distinguished Prof David Tissue, Prof Zhonghua Chen, A/Prof Oula Ghannoum, Dr Chris Cazzonelli, Dr Sachin Chavan, Prof Ian Anderson, Dr Nisha Rakhesh, Mr David Thompson	Learn and adapt, modify as we move and also provide accountability to funders and levy payers
Hort Innovation (Primary)	Feedback to stakeholder Justification for levy payers Feedback into HIA plan
Secondary	
Glass house industry	Energy/cost savings Water savings Drive to have food production closer to urban cities Decisions for future investment.
Dept of Agriculture	Return on investment
Smart glass industry	Research findings and implications Potential for commercialisation.
University	Public interest
General public	Food produced sustainably.
Syngenta and other private companies	Potential for commercialisation

b) Key Evaluation questions

Table 2: Project key evaluation questions

Key evaluation questions	Relevant?	Project-specific questions
Effectiveness		
1. To what extent has the project achieved its expected outcomes?	Hypothesis-Savings in energy without impacting productivity	Has the project developed new technology that is now available for industry uptake? The project delivered evidence based information for the use of SG in commercially important vegetable fruit and leafy vegetable crop cultivars and identified key issues with current SG technology. The project provided recommendations to design a suitable cover material as the current SG reduces energy and nutrient use at the cost of yield losses. The project has helped establish foundation for crop trials under innovative cover materials and initited crop trails for a new promising commercial film LLEAF.

Key evaluation questions	Relevant?	Project-specific questions
Relevance		
2. How relevant was the project to the needs of intended beneficiaries?		To what extent has the project met the needs of Glass house/Protected cropping and veg levy payers? High energy cost is a major issue for greenhouse operations, limiting the productivity and profitability of horticulture businesses across Australia. The project has provided extensive information to analyse cost/benefit ratio for key vegetable crop production under SG.
Process appropriateness		
3. How well have intended beneficiaries been engaged in the project?		Have regular project updates been provided? How accessible were extension events to industry levy payers? The project results and updates were made publicly available in journal articles (Chavan et al; 2020, Zhao et al; 2021, He et al ; 2021), magazine articles (Vegenote, Future Makers, CRC Future Food Systems) and open forum articles ensuring the outreach to a wide audience including the growers and industry partners (see appendix 5). The intended beneficiaries were also effectively engaged through steering committee meetings, grower discussions and masterclass which allowed to get the feedback from beneficiaries (see appendix 4).
Efficiency		
5. What efforts did the project make to improve efficiency?		How project has adapted to maximise benefits? What influence is this having on profitability and productivity? The project involved result driven changes in crop selection and treatment modification. After negative impact of SG on eggplant yield, relatively small sized fruit crop capsicum and leafy vegetable crop lettuce were tested under SG. Climbing vine fruit crop capsicum and leafy vegetable crop lettuce selection along with CO_2 increase during second capsicum trial allowed to distinguish between light quantity and quality role in reduction of yield under SG. Data acquired for detailed light quality characterisation and molecular changes in harvest quality will be useful in potential use of light altering cover materials in developing nutrient rich crops. The SG proved somewhat neutral as there was yield loss associated with energy and resource use savings under SG. However the project has initited crop trails for a new promising commercial film LLEAF.

Performance expectations, data collection and analysis

Table 3 Project monitoring plan

Logic level	What to monitor (see logic)	Performance expectation (KPIs) and/or monitoring questions	How to monitor (suggested methods)	Data collection – method and source	When	Responsibility (who is responsible for the monitoring and how will results be reported)
Foundational activities (list)	***Project planning*** SG installed, Baseline data collected Steering committee established	Baseline data without plants in the glass house collected and analysed Steering committeee established	Activities recorded	Glasshouse facility equipped with PRIVA was used to collect baseline data	Before the start of experimental trials on crops	Results were reported six months after project intiation
Activities and outputs (list)	• Sensors Installed • Three crops were grown for two or more experimetns under SG • Light changes, growth, yield and quality parameters were measured • Students, casual workers and early career researchers were trained • Industry engagement was achieved through interactive workshops , field days and demonstrations, publications and training (masterclass)	Data were successfully collected and some of the data analysis is still underway Extension of research results was achieved through engagement and magazine articles (appendix 4)	Activities and observation were recorded	Data were collected for SG effect on light using advanced sensors and on growth, physiology, biochemistry and yield using advanced analytical instruments and techniques along with the suggestions by expert growers and industry advisors	Data were collected throughout the project duration as required for evaluation	Project team and steering committee updates Milestone reports, Annual reports, Industry reports, magazine articles and publications were provided on regular basis.

Intermediate outcomes (list)	Results on crop trials updated through magazine sand journal articles. Six monthly milestone reports provided on smart glass trials.	Growers were updated with SG project results to make informed decisions for modifying/developing facilities.	Participatory group discussions coducted during event days and field site visits.	Preliminary results discussed with growers an advisors.	Data were collected throughout the project duration as required for evaluation	Intermittent (Project Team member) Independent reviewer Milestone Reports, Final Reports, Industry reports, magazine articles and publications were timely provided.
End-or-project outcomes (list)	SG engineering reccomonded to improve cost benefit ratio. SG project successfully helped to etablish infrastructure for future protected cropping research and trained workforce to manage production in glasshouse and perform cutting edge research.	SG saved energy at the cost of productivity The project improved understanding on SG technology Cost benefit analysis is underway Trained workforce will be useful to manage production in glass house and enabling Australia to globally compete in energy saving solar and glasshouse production and commercialisation of innovative glass technologies	Data on crop growth collected and analysed at regular intervals. Data analysis for last experiments and compreheinsive energy analysis is still underway. Participatory group discussions coducted during event days and field site visits.	Experiments were successfully conducted to test a range of crops in different light conditions. Preliminary results discussed with growers and advisors.	Data were collected throughout the project duration as required for evaluation	Organisation/specific project team member Independent reviewer Final report including yield and growth response to SG is being submitted. However, the huge data collected during experimetns will require more time for complete analysis.

Evaluation

Table 4 Additional evaluation data requirements

KEQ	Data collection requirement	Source and method
To what extent has the project achieved its expected outcomes?	Our hypothesis here is savings in energy without impacting productivity. Data were successfully collected for • The light irradiance and spectrum change due to SG • The temperature change due to SG • The humidity change due to the instrallation of the SG • Plant response to the environmental changes including the productivity and the usage of the nutrient. • Energy consumption change including the energy cost of heating and cooling	We successfully tested the project hypothesis and found that the SG energy savings come at the cost of yield losses. More compreshensive energy and cost benefit analyses are underway.
How relevant was the project to the needs of intended beneficiaries?	Data were successfully collected for • Profitability (like increased energy use efficiency, minimised energy costs). • Productivity (like high yield and improved quality). • Global competitiveness (like skill development in solar and glass house production) • Increased knowledge and improved understanding on the best practice with associated cost benefit data;	The project has helped to establish the state-of-the-art facilities to test and evaluate new crop varieties and technologies to minimise energy costs and maximise production. Protected cropping is the fastest growing food-producing sector in Australia and the SG project is directly associated with beneficiaries aiming to reduce the cost of production through the use the innovative glass technologies in horticultural crop prodiction. The outcomes of the project have increased knowledge and improved understanding on the the use of innovative SG.
How well have intended beneficiaries been engaged in the project?	Study the quality of engagement through extension and training programmes	The reviews on crop monitoring and target crops in protected cropping involved collecting information through group discussions and questionnaires along with discussions with growers during masterclass, workshops and trainings (appendix 4 and 5). The results were also extended through number of quality science

		and communication articles published in high impact factor journals and industry magazines. The intended beneficiaries participated in monitoring research progress through steering committee meetings, field days, master classes etc. The beneficiaries were updated with research updates through newsletters and peer reviewed journal articles.
What efforts did the project make to improve efficiency?	Identify measures to adapt to maximise benefits. How best resources are used to deliver the best? How flexible the project is made to suit levy payers needs?	How many times information from steering committee and other industry committess have been taken on board and the project modified accordingly? The suggestions and conlcusions in the steering committee meeting were utilized while progressing with the research project. The crop selection and treatments were modified to investigate the in depth SG impact in order to provide broad reccomdations on use of SG.

Table 5 Independent evaluation studies

Type of evaluation	When (start and finish)
Mid-term evaluation	*1/11/2018-1/12/2018*
Final evaluation	*11/03/2020-11/04/2020*

6. Reporting, learning and improvement

Table 6 Project progress reporting

Report type	To whom	Timing
Milestone Reports	Hort Innovation	Six-monthly
Final Reports	Hort Innovation	At end of project
Articles	Industry magazine	Annually
Written and verbal update	Project Reference Group	Six-monthly
Financial reports	Project Partners	Annually

Table7 Project continuous improvement activities

Continuous improvement process	Details	Timing
Reflection meeting with Hort Innovation R&D Manager	Meeting between R&D Manager, SUT and WSU researchers to discuss progress to-date and what’s working well/not, and agree any follow up actions	Six-monthly

Team meetings	Meeting between project team members from SUT and WSU to discuss project trials and their timing. Meeting between project team members to discuss feedback from extension event participants to determine gaps in adoption and preferred learning styles for incorporation into project	Quarterly
Project Steering committee meetings	Meetings between project team members, Hort Innovation and industry representatives to gain feedback on project activities and refine methodology	Six monthly

Recommendations

Based on the extensive experimental trials conducted in this project, we provide the following recommendations to the Australian vegetable growers and HIA:

- Current SG reduces energy and resource use, but also reduces yield in all crops (eggplant, capsicum and lettuce). However, it does not significantly affect quality. A cost-benefit analysis would be required to determine the value of current SG for specific crops.

- The yield (mass production) of leafy vegetable crops (lettuce) is less negatively affected by SG relative to fruiting vegetable crops, potentially due to sensitive source-sink regulation in fruit crops.

- SG alters color and pigmentation, especially in leafy vegetable crops, which could be useful targets to produce nutrient-enriched vegetables and fruits.

- Elevated CO_2 partially compensates for the negative impact of SG on yield in some crop genotypes, which suggests that a cost-benefit analysis should be developed to determine whether the cost of eCO_2 is lower than the cost of the SG film and energy savings.

- Vegetables with higher light use efficiency or shade tolerant vegetables (e.g. cucumbers) and herbs (e.g. parsley, basil) may perform better in energy saving cover materials like SG that decrease light penetration.

- Using data generated from this project, current SG should be re-engineered to increase UV and Red light penetration, and further reduce IR penetration, to increase PAR and crop yield.

- Additional light films should be trialed, so we have begun to use LLEAF-Red films developed by an Australian start-up company, which show promise to increase crop yield.

- Films with light-shifting properties should continue to be developed to reduce energy, water and nutrient use, while maintaining yield and quality. There is certainly promise in this area.

Refereed scientific publications

Journal article

B Rabbi, ZH Chen, S Sethuvenkatraman (2019) Protected Cropping in Warm Climates: A Review of Humidity Control and Cooling Methods. Energies 12, 2737

Chavan S, C Maier, Y Alagoz, J Filipe, C Warren, H Lin, B Jia, ME Loik, C Cazzonelli, Z Chen, O Ghannoum and DT Tissue. 2020. Light-limited photosynthesis under energy-saving film decreases eggplant yield. *Food and Energy Security* doi:10.1002/fes3.245.

Samaranayake P, W Liang, ZH Chen, DT Tissue and YC Lan. 2020. Sustainable protected cropping in Australia: energy consumption and crop yield analyses of greenhouse capsicum production. *Energies* 13: 4468. doi:10.3390/en13174468.

Zhao C, S Chavan, X He, M Zhou, C Cazzonelli, Z Chen, DT Tissue and O Ghannoum. 2021. Smart film impacts stomatal sensitivity of greenhouse capsicum through altered light. *Journal of Experimental Botany* 72: 3235-3248. doi/10.1093/jxb/erab028/6115786

He X, C Maier, SG Chavan, CC Zhao, Y Alagoz, C Cazzonelli, O Ghannoum, DT Tissue and ZH Chen. 2021. Light-altering cover materials and sustainable greenhouse production of vegetables: a review. *Plant Growth Regulation* doi.org/10.1007/s10725-021-00723-7

Chavan SG, ZH Chen, O Ghannoum, CI Cazzonelli and DT Tissue. 2021. Protected cropping: current technologies and target crops. *CRC Future Food Systems*. https://www.futurefoodsystems.com.au/wp-content/uploads/2021/04/P2-004-Protected-cropping.pdf

Maier C, ZH Chen, CI Cazzonelli, DT Tissue and O Ghannoum. 2021. Smart crop monitoring: Precise phenotyping for improved quality and protected cropping management. *CRC Future Food Systems*. https://www.futurefoodsystems.com.au/wp-content/uploads/2021/04/P2-005-Smart-crop-monitoring.pdf

Terry Lin, Mark Goldsworthy, Sachin Chavan, Wei Liang, Chelsea Maier, David Tissue, Yi-Chen Lan, Subbu Sethuvenkatraman*, Zhong-Hua Chen. Seasonal Variations in Temperature and Irradiance Determine Differential Eggplant Yield under Energy-saving Smartglass (In preparation for *Energy*)

Chavan, S.G., Xin He, Maier, C., Alagoz, Y., Cazzonelli, C.I., Chen, Z., Ghannoum, O., Tissue, D. “Responses of Capsicum growth, photosynthesis, yield, fruit quality and resource use to the Smart Glass”. (In preparation).

Chavan, S.G., Zhao, C; Vandegeer, R; Maier, C., Cazzonelli, C.I., Chen, Z., Ghannoum, O., Tissue, D. “Interactive effects of elevated CO2 and Smart Glass on Capsicum growth, photosynthesis, yield, fruit quality and resource use”. (In preparation).

Book chapters

P Samaranayake, G Lopaticki, W Liang, V Tam, ZH Chen, YC Lan. (2021). Process Modelling for an Efficient and Dynamic Energy Consumption for Fresh Produce in Protected Cropping. EcoDesign and Sustainability II, 361-370

A Evangelista, YC Lan, ZH Chen, VWY Tam, R Datt. (2021). Adopting Life Cycle Assessment for

Various Greenhouse Typologies in Multiple Cropping Environment in Australia. EcoDesign and Sustainability II, 347-360

Datasets

Chavan, Sachin; Maier, Chelsea; Alagoz, Yagiz; Filipe, Joao; Warren, Charles; Cazzonelli, Chris; Chen, Zhonghua; Ghannoum, Oula; Tissue, David, 2020. "Response of eggplant growth, photosynthesis, yield and fruit quality to Control and Smart Glass treatments in a glasshouse facility located at Western Sydney University during a 2-year period (2018-2019)", Mendeley data, http://dx.doi.org/10.17632/h225w9kvmr.1.

PRIVA and additional data-logger datasets for light and growth environment parameters are uploaded on servers for all three crops and seven growth cycles. We will make these be publicly available (if allowed) when we publish the manuscripts for crop trials under SG.

Magazine articles

VG16070 – Research and operations to trial innovative glass and photovoltaic technologies in protected cropping (2019).
https://ausveg.com.au/app/uploads/2019/12/AUSVEG_Vegenotes_Summer-2019_75_F01v1.pdf

Bringing agriculture indoors (2020). https://www.nature.com/articles/d42473-020-00069-0

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Chavan, S. G., Cazzonelli, C. I., Chen, Z. H., Ghannoum, O., & Tissue, D. T. (2020).

Review on "Current Technologies and Target Crops in Protected Cropping" submitted to Future Food Systems CRC (will be published shortly)

Maier, C., Cazzonelli, C. I., Chen, Z. H., Tissue, D. T & Ghannoum, O. (2020). Review on "Precise Phenotyping for Improved Crop Quality and Management in Protected Cropping" ubmitted to Future Food Systems CRC (will be published shortly)

Lin, K.-T., Lin, H., & Jia, B. (2020). Plasmonic nanostructures in photodetection, energy conversion and beyond. *Nanophotonics*, *9*(10), 3135–3163. https://doi.org/10.1515/nanoph-2020-0104

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Rigby, E. (2019). Protected cropping in subtropical climates. *A report for Nuffield Australia Farming Solutions.* Retrieved from: https://nuffield.com.au/emily-rigby-2/ [Online Resource]

Roser, M., & Ritchie, H. (2019) - "Yields and Land Use in Agriculture". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/yields-and-land-use-in-agriculture' [Online Resource]

Smith G (2020). An Overview of the Australian Protected Cropping Industry. Retrieved from https://www.graemesmithconsulting.com/index.php/information/general-industry-information

Intellectual property, commercialisation and confidentiality

Acknowledgements

Appendices

1. Appendix 1: Eggplant trial
2. Appendix 2: Capsicum trial
3. Appendix 3: Lettuce trial
4. Appendix 4: SG project engagements
5. Appendix 5: SG project articles (Attached separately)
6. Appendix 6: Talk on “Protected Cropping: Use of Smart Glass to reduce energy cost in future climates” in One-Week International Online Training Programme “Advance Digital and Biotechnological Tools in Modern Agriculture” (2020) organised by Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharshtra, India. (Attached separately)

Appendix 1: Eggplant trial – comprehensive energy analysis

The detailed results along with for eggplant trial are available online in the journal *Food and Energy Security* (Chavan et al 2020). Here we report the preliminary results for comprehensive energy use analysis for the eggplant trial. Initial results show that SG reduces chiller energy usage by 12% from mid-summer through to mid-winter, and by 4% from early spring through to early autumn; increased active venting by 28.75% in cooler months; and decreased nutrient and water usage by over 20% in both experiments. The results indicate that greenhouses that use SG panels may benefit from strategic planning of many facets of greenhouse operation, including fertigation strategy, curtain operation, and cooling modality.

The impact of glass selection upon chiller activity was examined through descriptive plots and regression. In contrast to control rooms, SG rooms reduced electricity spent on chilled water across experiment-1 (-11.16%) and experiment-2 (-4.10%) (Figure 1). Additionally, experiment-2 chillers used more electricity (86.48%) overall as the experimental duration overlapped with summer and spring, whereas experiment-1 had lower light levels and temperatures as the primary seasons involved were autumn and winter. Similarly, linear regression for total outside irradiance vs daily chiller energy usage revealed a good correlation ($R^2 = 0.86 – 0.89$) with solar radiation, with both SG rooms using less energy per kWh irradiance and a lower solar radiation activation threshold for chillers in experiment-2 (Figure 2).

The peak for outside temperature arrived at approximately 3PM, and chiller energy usage deviated for SG versus control rooms after around 11 AM (Figure 2). Conversely, the peak for chiller energy usage was at around 1PM, describing situation between distinct solar and temperature maxima. Chillers were typically active between 7:30 AM and 7:30 PM on a typical day, however cook’s difference-plots identified impactful outliers for days where air temperatures remained homogeneous into the night, e. g. due to easterly winds; during analysis, these subsets were typically indistinguishable from days with more heterogeneous temperatures.

Linear regression for measured PAR vs daily chiller energy usage revealed two distinct clusters in the data which reflected the curtain control strategy (Figure 3). As a result of this active removal of heat and obstruction of solar heating by greenhouse climate controls and barriers, the daily heating regime could be delineated into two primary mechanisms: 1) direct heating of greenhouse air from solar radiation, and 2) indirect heating through convection and conduction, with shaded periods during experiment-2 chiefly involving the latter mechanism.

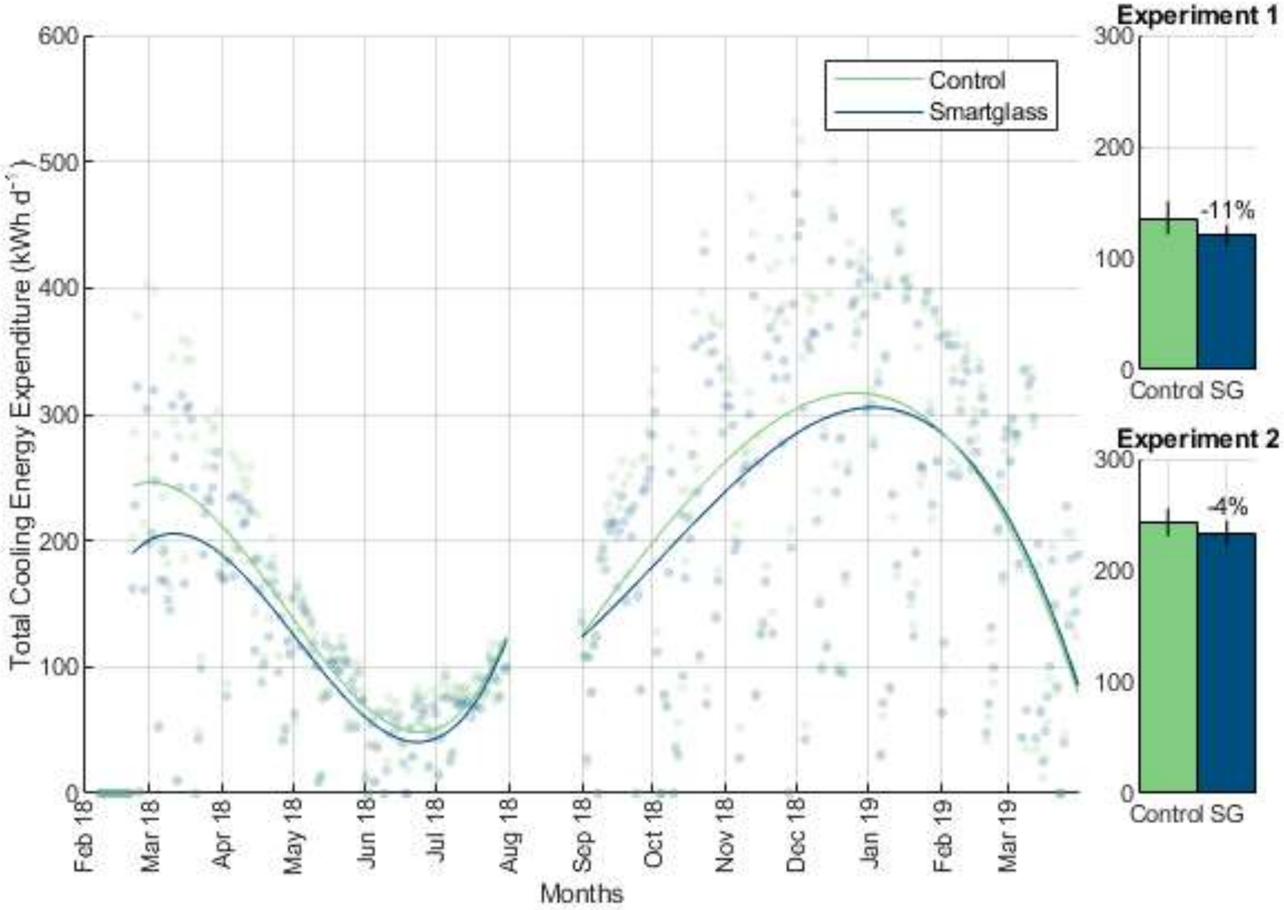

Figure 1 Smart Glass (SG) reduced cooling energy expenditure in both experimental periods, with a stronger effect in cooler months. A) Frequency distribution plots for measured cooling energy expenditure, averaged for both SG and control groups. Data was amplitude-normalized to account for differing experimental durations, and curves were fitted via kernel smoothing. Energy expenditure in experiment-2 reflects the higher climate variability observed during warmer months. B) Measured total daily cooling energy expenditure, averaged for SG and control groups. Left panel (a) represents data as a scatter plot for both experiments 1 and 2, where polynomial fits start from Feb 22 to account for missing data. Data is represented as a bar plot of means in (b) and (c) for experiments 1 and 2 respectively; error bars represent 95% confidence intervals.

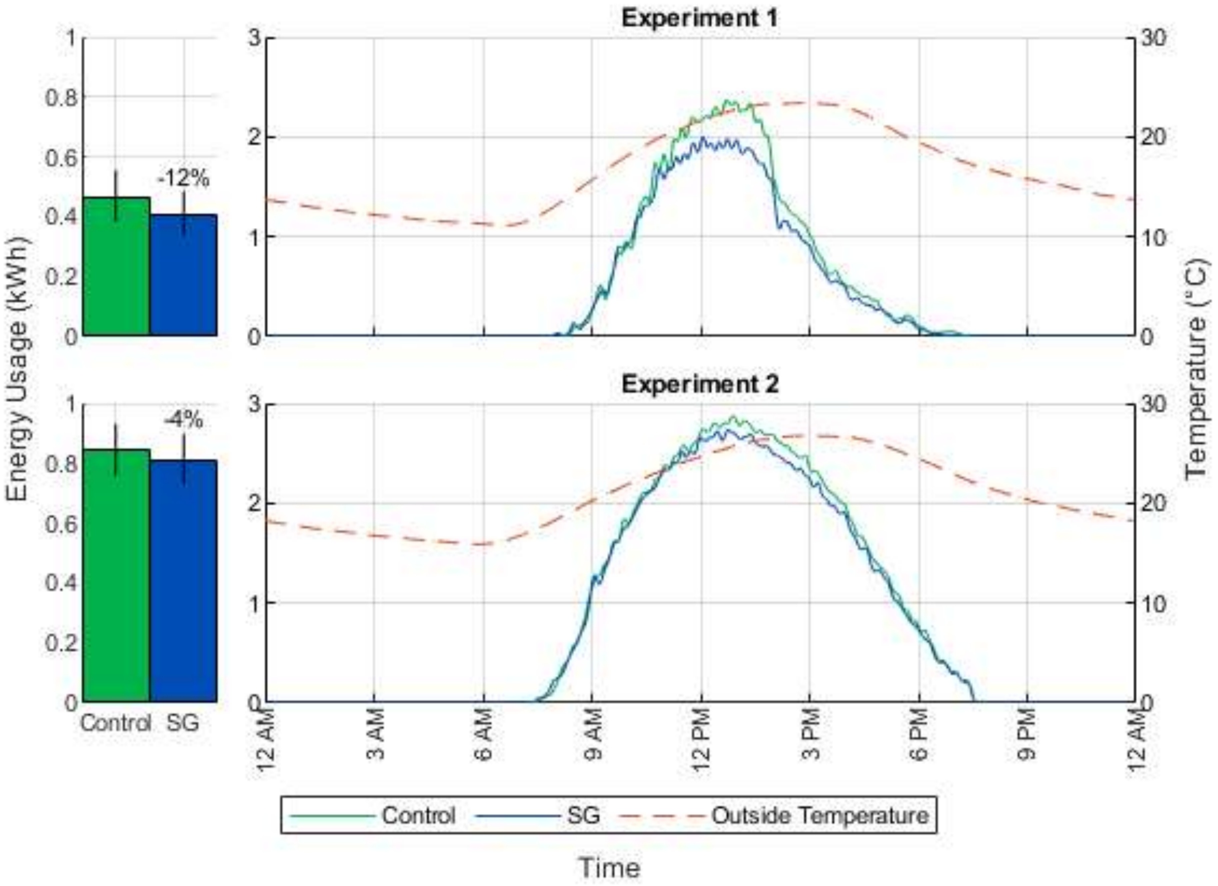

Figure 2 Energy expenditure generally deviated after 11 AM and peaked at 1PM, coinciding with the sun's elevation to approximately 75 - 90° overhead, whereas temperature maxima appeared closer to 3PM. Data is represented via bar plots of daily means in (a, c) for experiments 1 and 2 respectively, with error bars representing 95% confidence intervals. Right panel (b, d) depicts 5-minute sampled cooling energy expenditure, averaged for SG and control groups to describe a typical experiment day, with smoothed spline fitting for both experiments 1 and 2.

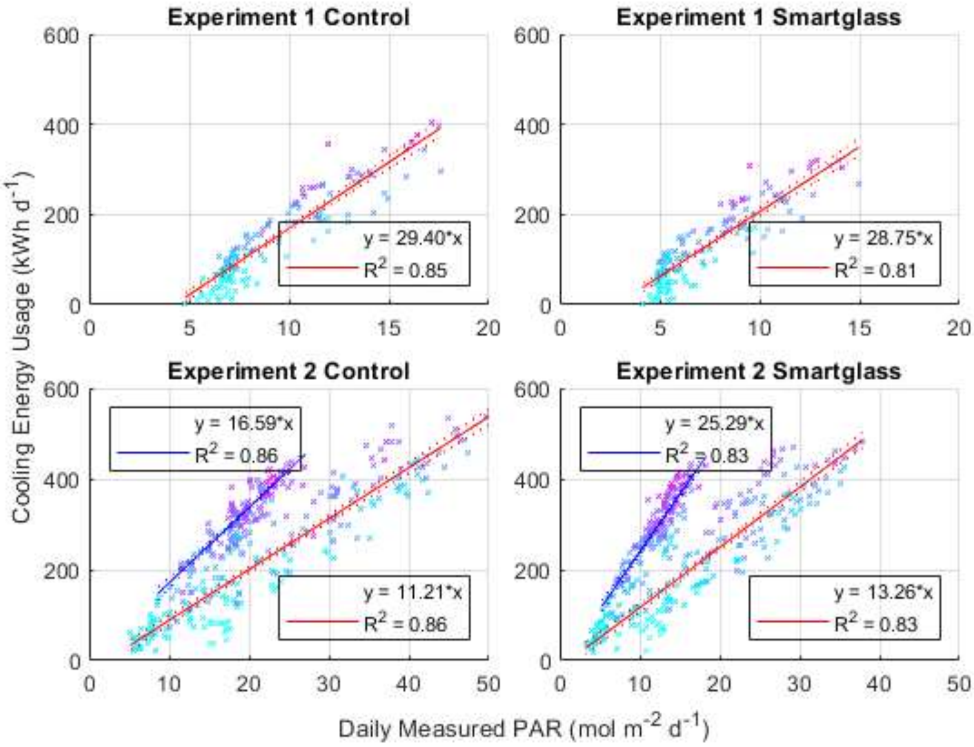

Figure 3 Linear regression described two clusters which identify the difference in curtain strategy between experiments, but which also highlight the distinct heating mechanisms in experiment-2. Linear regression for total daily cooling energy expenditure versus measured PAR at top-canopy level. Darker scatter value intensities indicate higher temperature differentials (maximum outside temperature – average greenhouse temperatures). Fits for experiment-2 were achieved after spectral clustering to delineate data into two clusters. Dotted lines depict 95% confidence intervals.

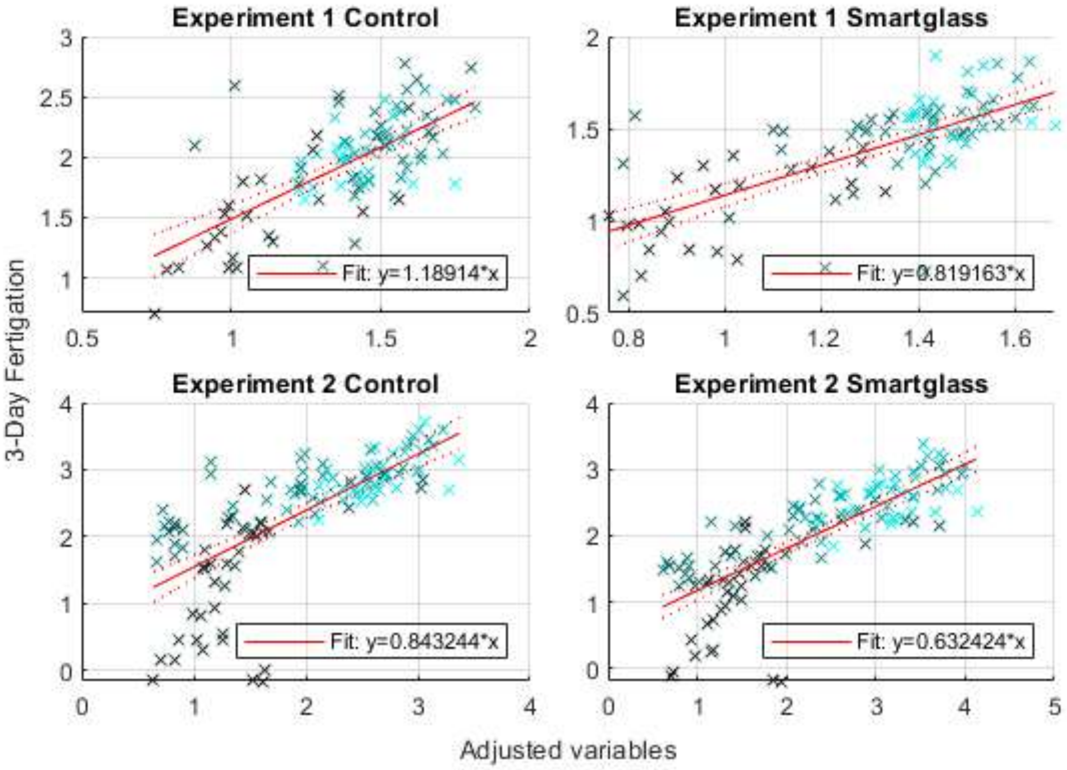

Figure 4 3-day fertigation was significantly lower for smartglass (SG) rooms across both experiments, and in Experiment-2 a distinct nonlinear component was found which corresponded well to expected plant growth. Added variable plot for multiple regression for 3-day irrigant consumption, with predictors 1) temperature difference (maximum outside temperature – average greenhouse temperatures), and 2) measured PAR at top-canopy level. Darker scatter intensities depict earlier experimental dates. Dotted lines depict 95% confidence intervals.

Appendix 2: Capsicum trial results

Smart Glass significantly decreased the light transmission except during low light conditions of winter:

Daily light integral (DLI) measured using PAR sensors at the canopy level showed variation in SG light transmission according to the light intensity in both experimental trials (Figure 1 and Figure 3, a-b). SG significantly reduced DLI during autumn, spring, and summer (Feb-May and July-Dec) with high light but not during the winter months (May-July) with lower light levels in both experiments (Figure 1). Seasonal variation in light coupled with differential transmission under SG depending on the light intensity created distinct light environments during experiment-1 and 2.

Experiment-1 started in low light conditions of Autumn (April 2019 with DLI around 10 mol m^{-2} d^{-1}), which was followed by low light period of winter (June and July with around 7.5 mol m^{-2} d^{-1}) and had no significant light differences between SG and Control compartments during the first half of the experiment. With the start of spring (August 2019) during the second half of the experiment, light intensity started increasing along with the differences in SG and Control until the end of experiment in summer (December 2019, with DLI around 20 mol m^{-2} d^{-1}). Consequently, SG significantly reduced DLI (-22.6%) during the second half of the experiment from August 2019 to December 2019. Experiment-2 started during high light conditions of summer (January with DLI around 15 mol m^{-2} d^{-1}) with significant light differences (-18.1% from January to April) but the light differences disappeared in the middle of growth experiment (May to July with DLI around 10 mol m^{-2} d^{-1}). However, the light differences appeared again at the end of experiment (Sep with DLI around 20 mol m^{-2} d^{-1}). Despite the variable light difference periods, SG similarly decreased average growth season DLI by -20.3% and -21.7% in experiment-1 and 2 respectively.

Morphological parameter response to SG differed in two experiments:

Height: During initial growth period, plants grown under SG had marginally lower height relative to Control, but SG did not affect the final plant height in both the experiments (Figure 2, a-b). In experiment-1, SG reduced plant height by -5.5% (p value <0.05) and -5.6% (p value < 0.05) at 33 days after transplanting (DAT) in Red and Orange cultivar respectively, but the height was similar in SG and Control plant after 118 DAT in both the cultivars. In experiment-2, SG significantly decreased the height (-6.0%, p value <0.05) before 65 DAT, and the plant height was constantly lower under SG than control with average -4.7% reduction in both the cultivars. Overall, both cultivars were similar in height and grew quicker during experiment-2 and were +44% and +26% ($P<0.001$, Table 1) taller relative to experiment-1 at the 33 DAT and final stage, respectively.

Bud number: SG significantly increased the number of buds before first harvest in both the experiments. The bud number of both the cultivars was +25.5% (p value <0.05) and +19.1% (p value <0.05) higher under SG at the 33 DAT in experiment-1 and 65 DAT in experiment-2, respectively. After the first harvest, SG significantly increased the bud number of both the cultivars in experiment-1 (+23.7% p value <0.01) but not in experiment-2 (Table 1). Overall, the average bud number of both the cultivars in experiment-2 was significantly higher than experiment-1 (+86%, p value <0.001). Both the cultivars generally had similar bud numbers except at 33 DAT in experiment-1 where Orange cultivar had +67% more buds than Red cultivar.

Flower number: Overall SG did not affect flower number except for some time points. For instance, SG increased flower number of Red cultivar by +35.3% (p value <0.05) and +56.1% (p value <0.01) at 118 DAT and 147 DAT stage in experiment-2 and experiment-1, respectively. Flower number was significantly higher (+132.3 %, p value <0.001) at 33 DAT stage and lower (-83.0%, p value <0.001) at 65 DAT stage in experiment-1 compared with experiment-2, but it was relatively similar after 118 DAT between both the experiments. Both the cultivars generally had similar flower numbers (while the average number of Orange flower in experiment-2 was significantly lower (-18.4%, $P<0.001$) than that in experiment-1.)

Developing fruit number: SG did not significantly affect the overall mean developing fruit number except for +10 % (p value <0.01) increase under SG in Orange cultivar during experiment-1. Among the individual time pints, SG significantly decreased (-20%, p value <0.05) the developing fruit number of Red cultivar in experiment-1 at the 185 DAT stage and increased the developing fruit number of the Red (+22% p value <0.01) and Orange (+40% p value <0.001) cultivar in experiment-2 at the 147 DAT stage. Overall, Red cultivar had 27% (p value <0.001) more developing fruits in experiment-2 relative to experiment-1. There was no significant difference between two experiments for Orange developing fruit number.

SG decreased yield more in experiment-2 with light differences at the start than experiment-1 with light differences at the end:

Initial growth and fruit development for the first harvest differed among the two experiments. The first harvest for experiment-1 (61 DAT) occurred 18 days earlier compared to experiment-2 (79 DAT) (Figure 2). The response of yield to SG varied among cultivars and experiments according to the seasonal variation in growth light (Figure 3). During monthly harvests, the average fruit weight (Figure 3), response to SG fluctuated due to the variable fruit development periods and management practices. While the pattern of monthly harvests was similar for two cultivars within each experiment, the two experiments showed different patterns. Experiment-1 showed significant reductions in yield in the middle (August 2019 after two months low light) and at the end of growth season (November 2019, when was the the big light difference between SG and Control) for both cultivars. However, experiment-2 showed mostly consistent negative impact of SG on yield on monthly harvests for Red cultivar and negative impact of SG on yield at the start (April 2020) and end of the season (September 2020) for Orange cultivar (Figure 3, c-f). There was a significant decreased after June, when there was the low light period and then yield increased with the PAR increase in experiment-2.

In experiment-1 with high light intensity and light differences in the second half of the growth season (Figure 3, a), SG marginally decreased average fruit number and weight in Red cultivar (-15.0 % p value <0.01 and -12.1% p value<0.05 respectively, Table 1) mainly at the end of growth season when light decreased under SG, but not in Orange cultivar (Figure 3, a, c, e and Figure 4). In contrast, experiment-2 had high light intensity and light differences at the start of the growth season (Figure 3, b). Moreover, SG significantly decreased mean fruit number and weight in Red (-31.5 % p value < 0.001 and -30.4% p value <0.01 respectively) and Orange (-19.1% p value<0.001 and -16.5% p value <0.001 respectively) cultivars (Figure 3, b, d, f and Figure 4) in experiment-2.

Despite overall reduction of fruit number and weight under SG, the proportion of marketable fruits was higher under SG. In experiment-1, marketable fruits significantly increased by +8.6% (p value<0.001) in Red and +6.7% (p value<0.01) in Orange cultivar. While there was an increasing trend for Red cultivar in experiment-1 and for both cultivars in experiment-2, the increase was not statically significant. Overall, the proportion of marketable fruits was 6.3% (p value <0.001) higher in experiment-2 compared to experiment-1.

Capsicum quality response to SG, experiment, and cultivar:

The effect of SG on Brix content was cultivar specific (P<0.001, Table 3). The Brix of Orange cultivar was significantly increased under SG (+4%, P<0.05) and (+28%P<0.001) in experiment-1 and experiment-2, respectively. Brix of Red cultivar significantly decreased (-26%, P<0.001) in experiment-2 but not experiment-1. Overall, the basic quality parameters including moisture, pH, as and firmness were not significantly altered by SG for both cultivars and experiments (Table 3). There was an obvious visual color difference between two cultivars. In Red cultivar, SG did not impact the color indexes in experiment-1 but significantly increased L* (lightness, +1.5%), a* (-greenness to + redness, +6.4%) and b* (-blueness to +yellowness, +39.2%) in experiment-2. In Orange cultivar, L*was significantly increased under SG (+1.5%) in experiment-2 and a* and b* were significantly reduced (-12.4%, P<0.001 and -12.6% P<0.05, respectively) under SG in experiment-1. In experiment 1, SG also reduced the ascorbic acid content by -8.7 % (P<0.001) and -14.1% (P<0.001) in Red and Orange cultivar, respectively.

SG did not affect light saturated photosynthetic parameters:

Light saturated CO_2 assimilation rates (A_{sat}) were not affected by SG in both experiments and both cultivars (Figure 5) but there were cultivar differences. The Orange cultivar had a significantly lower (-9.9% $P<0.001$) A_{sat} relative to the Red cultivar. Stomatal conductance (g_s) varied according to the treatment, cultivar and experiment but the changes were not consistent. However, modelled CO_2 assimilation rates (A_{model}) at mean canopy growth light was significantly lower (-7% to -17%) under SG in both cultivars and experiments.

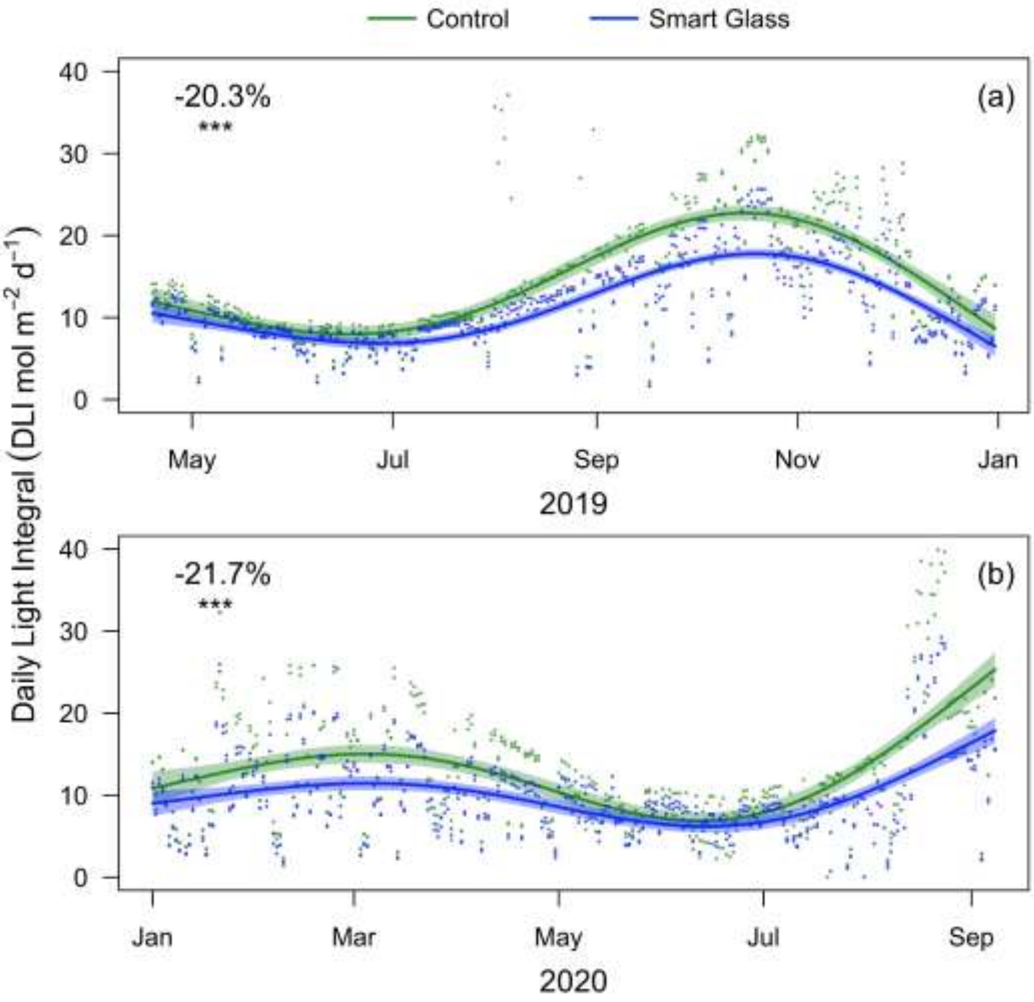

Figure 1. Smart Glass (SG) decreased the light transmittance more during high light conditions creating distinct light environment in two experimental trials. Panels a and b depict smooth plot of daily light integral (DLI, total daily PAR) over time measured during experiment-1 (from 2019/04/19 to 2019/12/19) and 2 (from 2020/01/20 to 2020/09/20) respectively. Points indicate DLI determined from five PAR sensors at canopy level. Control and SG treatments are depicted in green and blue, respectively. Light green and blue shades along mean lines indicate 95 % confidence intervals. The % difference in mean experimental DLI is depicted with significance levels indicated by *.

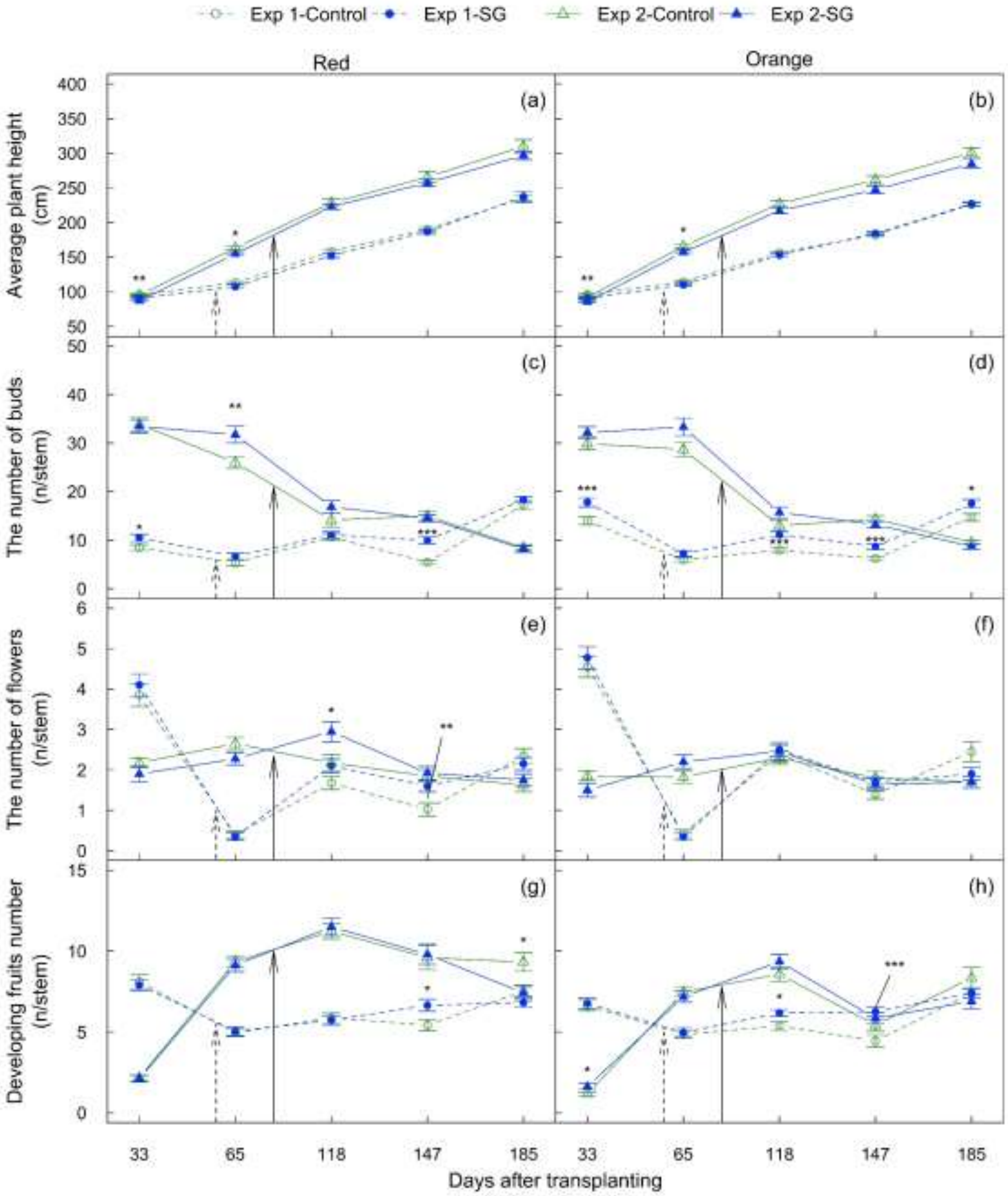

Figure 2. Effects of Smart Glass (SG) on morphological parameters in Red and Orange capsicum cultivars during two experimental trials. Panels a and b depict cumulative stem height, c and d depict number of buds, e and f depict number of flowers and g and h depict number of developing fruits over time. Control and SG treatments are depicted in green and blue, respectively. Circles and triangles represent experiment-1 and 2, respectively. Error bars indicate standard error (SE, n=20) of mean. The dashed and solid arrows indicate the harvest time in experiment-1 and 2, respectively. Statistical significance levels (*t*-test) for SG effect are shown: **P*<0.05; ***P*<0.01: ****P*<0.001. (levene test, P>0.05)

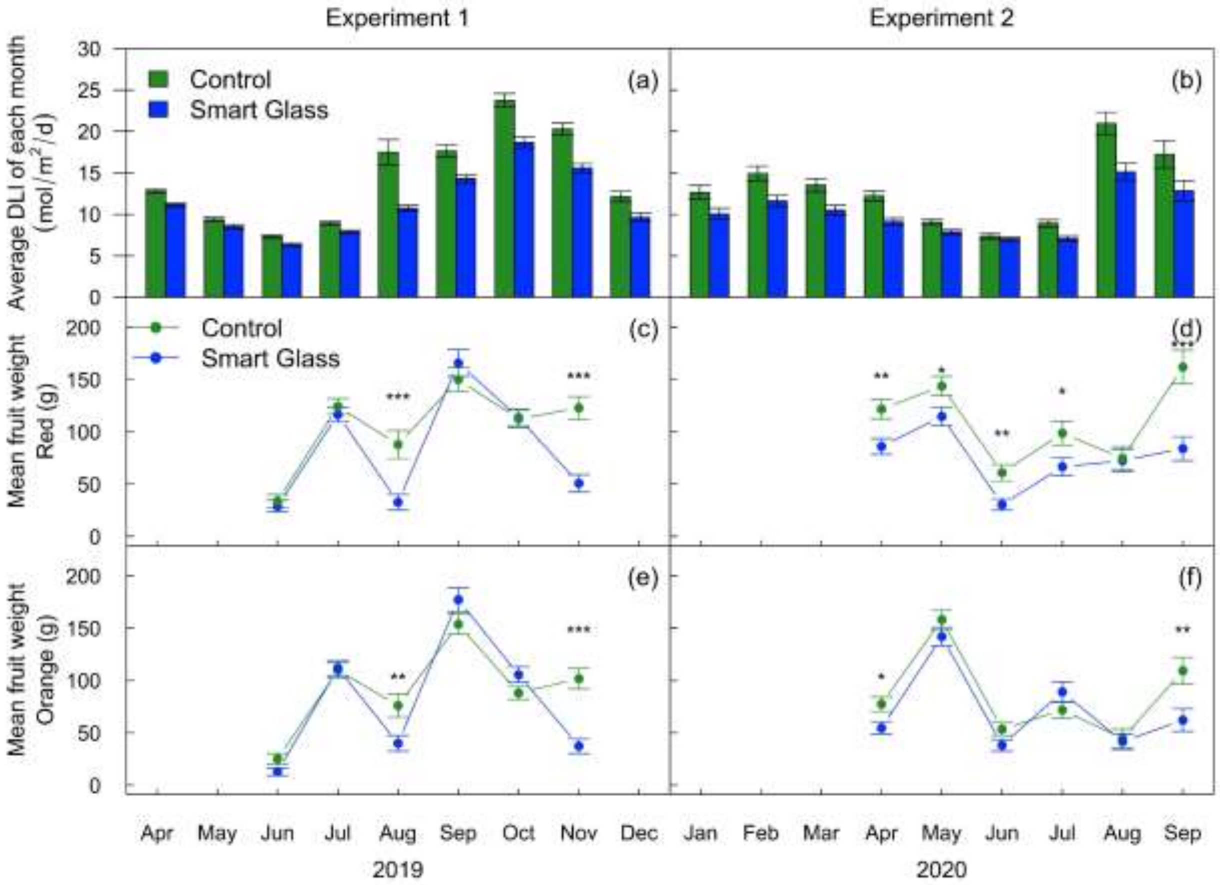

Figure 3. Light reduction under Smart Glass (SG) during early growth period decreases yields more than other developmental stages. Panel a and b depict the bar plots of monthly means for canopy level DLI during experiment-1 and 2, respectively. Circles in panel c and d depict the monthly means for fruit weight in Red cultivar during experiment-1 and 2, respectively. Circles in panel e and f depict the monthly means for fruit weight in Orange cultivar during experiment-1 and 2, respectively. Error bars indicate standard error of mean. Control and SG treatments are depicted in blue and red, respectively. Statistical significance levels (*t*-test) for SG effect are shown: *P<0.05; **P<0.01: ***P<0.001.

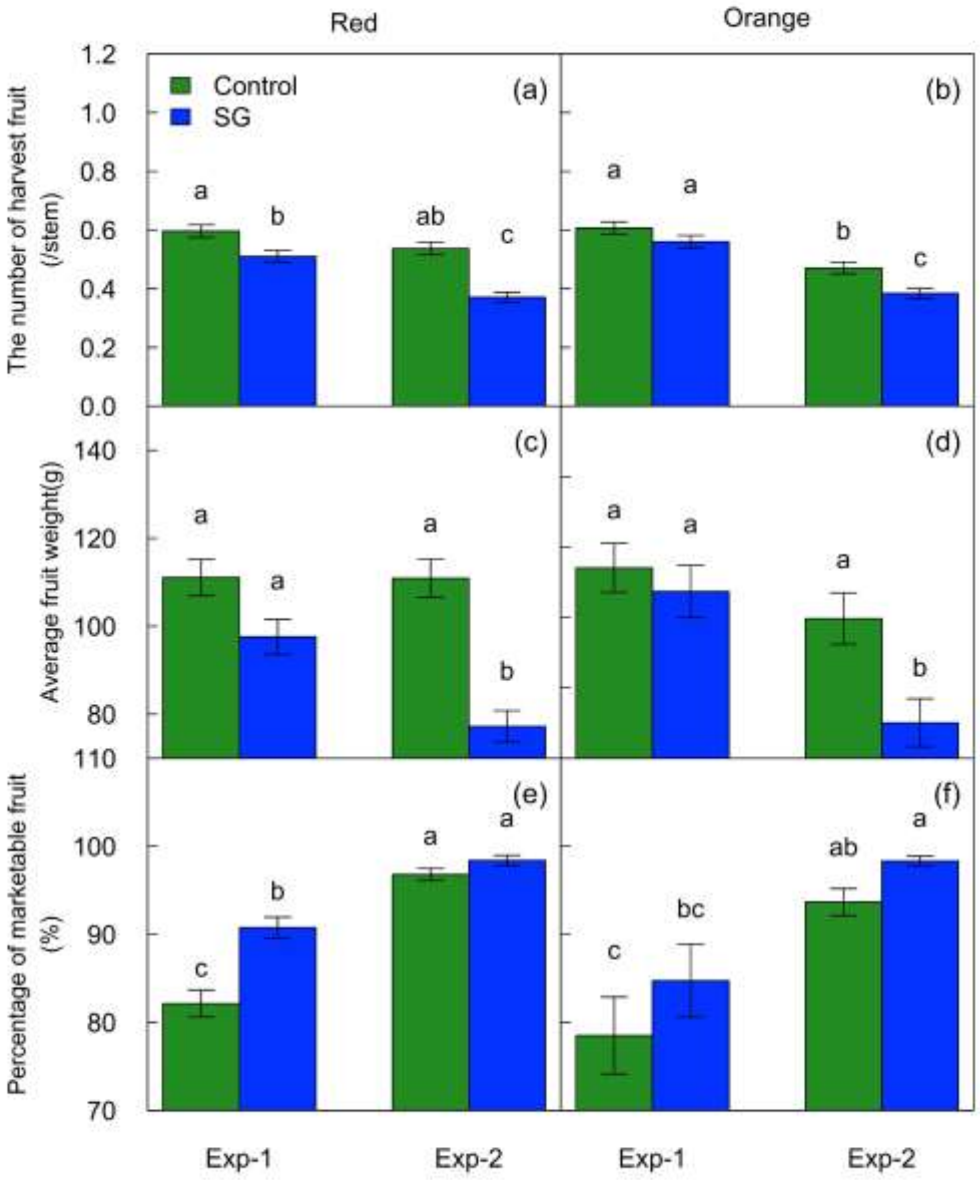

Figure 4. Smart Glass (SG) reduced the fruit number and average fruit weight but increased the percentage marketable fruits. Bar plots depict the mean fruit number (a and b), average fruit weight (c and d) and percent marketable fruit (e and f) for Red and Orange cultivar, respectively. The error bars indicate the standard error (SE) in each harvest month (n>120) of each month. The percent change ("-" or "+") in response to SG are shown at the top of bars. Control and SG treatments are depicted in green and blue, respectively. Bars sharing the same letter in the individual panels are not significantly different according to Tukey's HSD test at the 5% level. Statistical significance levels (*t*-test) for SG effect are shown: **P*<0.05; ***P*<0.01: ****P*<0.001.

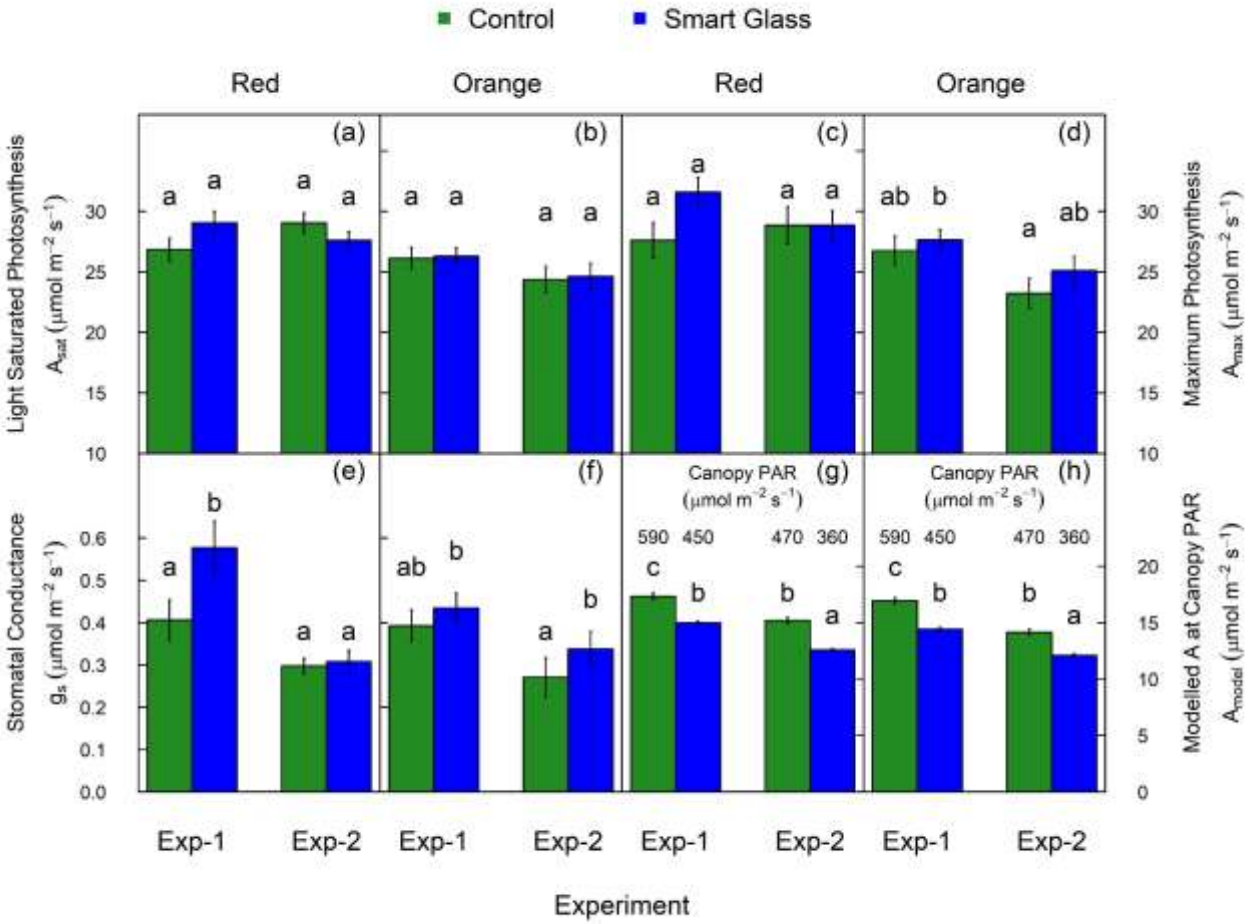

Figure 5. SG did not affect light saturated photosynthesis but reduced photosynthetic rates measured at growth light in both experiments. Bar plot of means for light saturated CO_2 assimilation rate (A_{sat}, a and b), maximum CO_2 assimilation rate (A_{max}, c and d) light saturated stomatal conductance (g_s, e and f) and modelled CO_2 assimilation rate (A_{model}, g and h) at the mean canopy level growth light in Red and Orange capsicum cultivars. Error bars indicate standard error of mean. Control and SG treatments are depicted in green and blue, respectively. Bars sharing the same letter in the individual panels are not significantly different according to Tukey's HSD test at the 5% level.

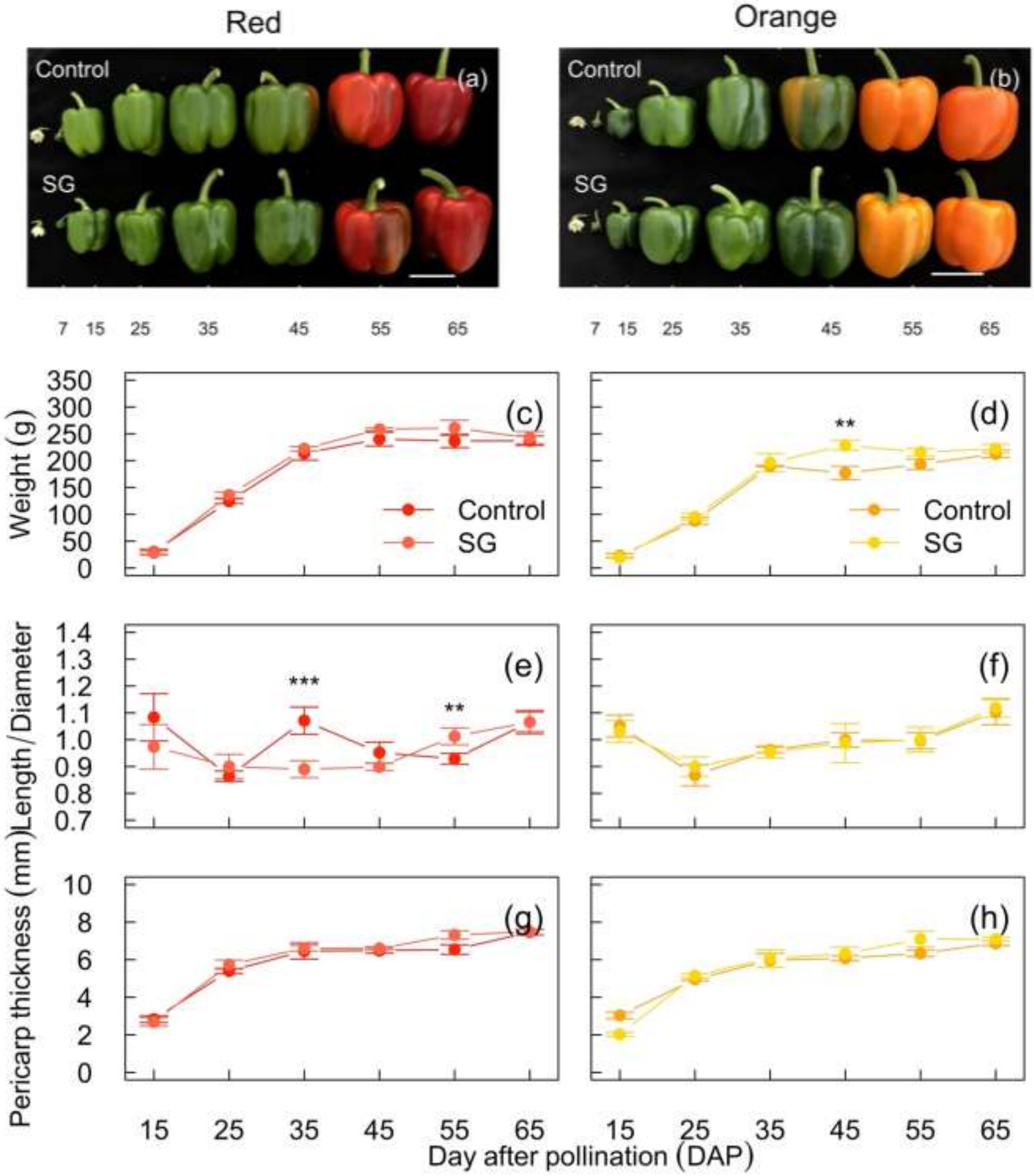

Figure 6. The dynamic fruit size and shape related traits changes among two cultivars under SG. Panel (a) and (b) depict the fruit development of red and orange under SG. Panels (c) and (d) fruit weight, (e) and (f) depict length/diameter and (g) and (h) depict pericarp thickness. Each value is the mean ± SE of 12 fruits. Bar = 5 cm. The significance levels for statistically significance differences were ns, *, **, and *** indicated P > 0.05, P ≤ 0.05, P ≤ 0.01, and P ≤ 0.001, respectively.

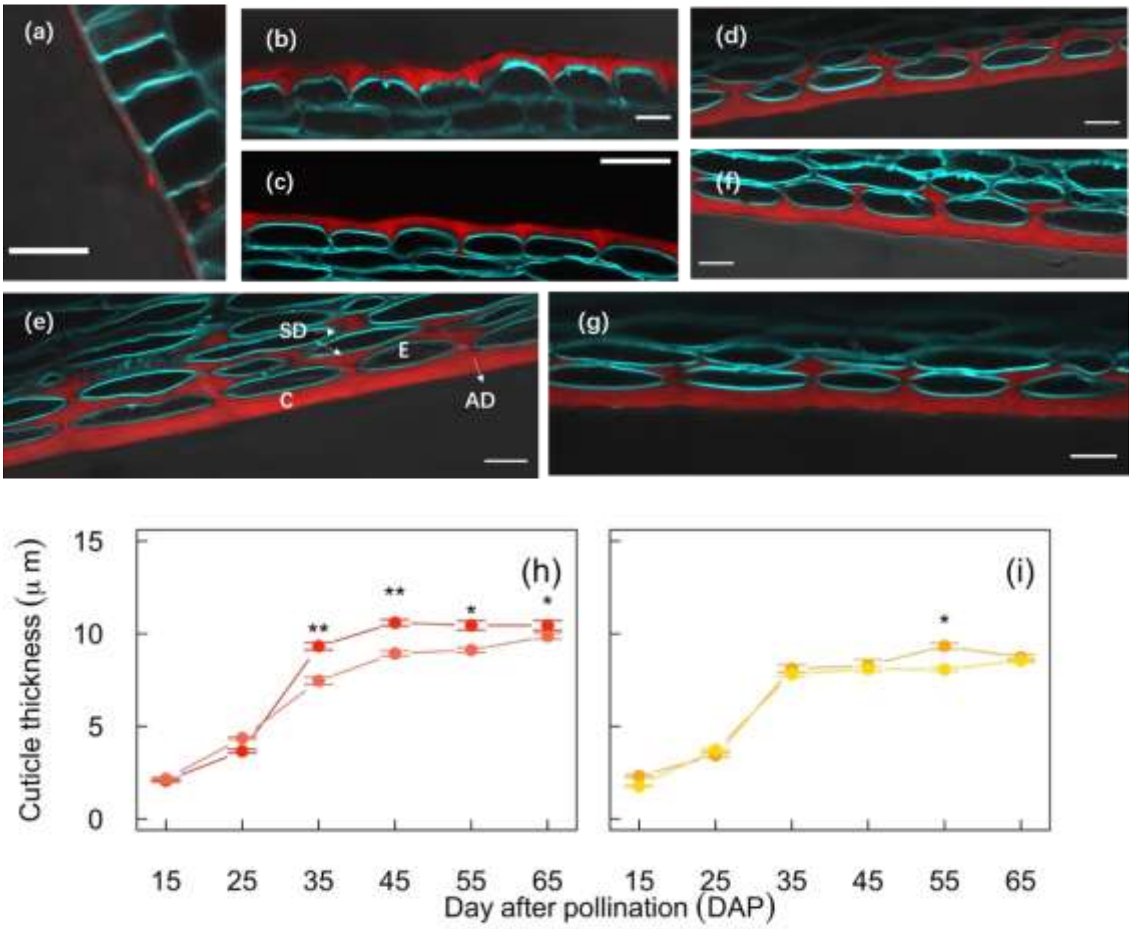

Figure 7. Confocal images showing the cuticle layer of fruit across different developmental stages. The lipophilic fluorescent dye Nile red for cuticle layer and cellulose dye Calcofluor White M2R were used to visualize the cuticle (red) and cell walls (blue). Scale bar=20 µm for all images. Panel (a) to (g) are cuticle layer in 7, 15, 25, 35, 45, 55 and 65 day after pollination, respectively. C, Cuticle; E, epidermal cell; AP, anticlinal peg; SD, sub-epidermal deposit. Panels (h) and (i) represent the cuticle thickness of each developmental stages measured "C" by ImageJ in the panel (e). The significance levels for statistically significance differences were ns, *, **, and *** indicated P > 0.05, P ≤ 0.05, P ≤ 0.01, and P ≤ 0.001, respectively.

Table 1. Summary of statistical analysis using one-way and two-way analysis of variance (ANOVA) for the SG and experiment effect on growth (n>24) and productivity parameters. The values represented are mean ± standard error of mean. *P* values are given, with significance levels *** *P*<0.001; ** *P*<0.01; * *P*<0.05; and NS, *P*>0.05. Individual average weight, the number of harvest fruit, marketable fruit (n>240), and

Parameter	**Exp**	**Red**		**Change (%)**	***P*-value**	**Exp *P*-value**	**SG*Exp**	**Orange**		**Change (%)**	***P*-value**	**Exp *P*-value**	**SG*Exp**
		Control	Smart Glass					Control	Smart Glass				
Growth parameters													
Height (cm)	1	235.73±4.	237.28±8.07	+0.7	NS	***	NS	226.02±2.	227.25±2.65	+0.5	NS	***	NS
	2	310.03±9.	296.94±6.07	-4.2	NS			300.83±6.	284.79±6.23	-5.3	NS		
Buds (n/stem)	1	9.45±0.42	11.31±0.40	+19.7	**	***	NS	9.76±0.37	12.49±0.44	+28	***	***	NS
	2	19.51±0.8	21.03±0.89	+7.8	NS			19.10±0.7	20.69±0.89	+8.3	NS		
Flower (n/stem)	1	1.86±0.12	2.06±0.12	+10.8	NS	NS	NS	2.25±0.13	2.25±0.13	0	NS	***	NS
	2	2.10±0.08	2.15±0.09	+2.4	NS			1.90±0.07	1.90±0.08	0	NS		
Developing Fruit (n/stem)	1	6.38±0.17	6.43±0.16	+0.8	NS	***	NS	5.74±0.15	6.32±0.13	+10.1	**	NS	NS
	2	8.34±0.32	9.94±0.31	+19.2	NS			6.20±0.27	6.17±0.24	-0.5	NS		
Fruit morphology and marketability													
Fruit Number (n/stem)	1	0.60±0.02	0.51±0.02	-15	**	***	*	0.61±0.02	0.56±0.02	-8.2	NS	***	NS
	2	0.54±0.02	0.37±0.02	-31.5	***			0.47±0.02	0.38±0.02	-19.1	***		
Fruit Weight (g/stem)	1	111.07±4.	97.58±3.95	-12.1	*	*	*	96.98±3.4	93.68±3.69	-3.4	NS	NS	NS
	2	110.91±4.	77.24±3.60	-30.4	***			89.83±3.6	75.05±3.41	-16.5	**		
Marketable Fruit (n/stem)	1	0.48±0.02	0.46±0.02	-4.2	NS	***	***	0.48±0.02	0.48±0.02	0	NS	NS	*
	2	0.52±0.02	0.36±0.02	-30.8	***			0.45±0.02	0.37±0.02	-15.6	**		
Marketable Fruit (%)	1	82.15±2.4	90.77±4.78	+8.6	***	***	**	79.90±2.6	86.55±1.63	+6.7	**	***	NS
	2	95.52±1.2	98.71±0.91	+3.2	NS			94.01±1.6	98.08±0.93	+4.1	*		
Large Fruit (>250g) (n/stem)	1	0.09±0.00	0.09±0.008	0	NS	NS	*	0.01±0.00	0.016±0.003	+60	NS	***	NS
	2	0.10±0.00	0.07±0.002	-30	**			0.04±0.00	0.03±0.002	-25	NS		
Unmarketable Fruit (n/stem)	1	0.021±0.0	0.010±0.00	-52.4	*	-	-	0.017±0.0	0.003±0.00	-82.4	***	-	-
	2	-	-	-	-			-	-	-	-		

Table 2. Summary of statistical analysis using one-way and two-way analysis of variance (ANOVA) for the SG and experiment effect on fruit quality (n=12) parameters. The values represented are mean ± standard error of mean. *P* values are given, with significance levels *** *P*<0.001; ** *P*<0.01; * *P*<0.05; and NS, *P*>0.05.

Parameter	Exp	Red		Change (%)	*P*-value	Exp *P*-value	SG*Exp	Orange		Change (%)	*P*-value	Exp *P*-value	SG*Exp
		Control	Smart Glass					Control	Smart Glass				
Total Soluble Solids (Brix)	1	6.61±0.06	6.62±0.11	+0.2	NS	***	NS	6.57±0.07	6.86±0.12	+4.4	*	***	***
	2	4.92±0.06	4.80±0.12	-2.4	NS			5.01±0.24	6.45±0.18	+28.7	***		
Titratable Acidity (citric acid, mg/g)	1	2.29±0.15	1.82±0.26	-20.5	NS	NS	***	2.00±0.15	1.84±0.26	-8	NS	***	**
	2	1.81±0.06	2.34±0.08	+29.3	***			2.23±0.07	2.63±0.10	+17.9	**		
Fruit color L*	1	70.57±0.28	70.56±0.22	-0.0	NS	***	NS	75.26±0.35	74.81±0.57	-0.6	NS	NS	**
	2	71.38±0.32	72.47±0.20	+1.5	**			74.51±0.19	75.65±0.24	+1.5	**		
a*	1	17.85±0.54	17.41±1.00	-2.5	NS	*	NS	16.97±0.93	14.87±0.21	-12.4	***	***	**
	2	16.22±0.25	17.26±0.40	+6.4	*			12.82±0.31	14.04±0.60	+9.5	NS		
b*	1	-1.07±0.28	-1.36±0.39	-27.1	NS	NS	NS	7.12±0.57	6.22±0.69	-12.6	*	***	NS
	2	-1.58±0.12	-0.96±0.27	+39.2	NS			4.06±0.27	4.66±0.42	+14.8	NS		
Moisture content (%)	1	92.93±0.08	93.15±0.11	+0.2	NS	***	*	92.39±0.05	92.14±0.08	-0.3	**	***	NS
	2	92.28±0.08	91.77±0.17	-0.6	NS			91.77±0.48	91.70±0.26	-0.07	NS		
pH	1	5.04±0.01	5.08±0.01	+0.8	***	***	**	5.06±0.01	5.05±0.00	-0.2	NS	***	NS
	2	5.35±0.01	5.31±0.01	-0.7	*			5.26±0.01	5.28±0.02	+0.4	NS		
Ascorbic acid (mg /100g FW)	1	91.81±6.84	83.81±3.67	-8.7	***	-	-	106.99±8.1	91.92±8.58	-14.1	***	-	-
	2	-	-	-	-			-	-	-	-		
Ash (g/100g)	1	0.32±0.00	0.32±0.00	0	NS	***	NS	0.31±0.00	0.33±0.00	+6.5	***	***	NS
	2	0.56±0.02	0.54±0.03	-3.6	NS			0.54±0.05	0.48±0.08	-11.1	NS		
Firmness (N)	1	12.87±1.30	11.26±1.00	-12.5	NS	**	NS	8.80±2.04	8.57±0.71	-2.6	NS	***	NS
	2	9.06±0.35	10.03±0.54	+10.7	NS			9.88±0.64	9.85±0.49	-0.3	NS		

Table 3 Summary of statistical analysis using one-way and two-way analysis of variance (ANOVA) for the SG and experiment effect on photosynthetic parameters. The values represented are mean ± standard error of mean. *P* values are given, with significance levels *** $P<0.001$; ** $P<0.01$; * $P<0.05$; and NS, $P>0.05$.

Parameter	**Exp**	**Red**		**Change (%)**	***P*-value**	**Exp *P*-value**	**SG*Exp**	**Orange**		**Change (%)**	***P*-value**	**Exp *P*-value**	**SG*Exp**
		Control	Smart					Control	Smart				
Light Saturated Photosynthesis Parameters													
A_{sat} $(\mu mol/m^2/s)$	1	26.85±0.92	29.06±0.96	+8.2	NS	NS	*	26.14±0.90	26.29±0.72	+0.6	NS	NS	NS
	2	29.06±0.83	27.61±0.72	-5.0	NS			24.36±1.07	24.64±1.08	+1.1	NS		
g_s $(mol/m^2/s)$	1	0.41±0.05	0.58±0.06	+41.5	*	***	NS	0.39±0.04	0.43±0.04	+10.3	NS	*	NS
	2	0.30±0.02	0.31±0.03	+3.3	NS			0.27±0.05	0.34±0.04	+25.9	NS		
Light Response Curve Parameters													
A_{max} $(\mu mol/m^2/s)$	1	27.61±1.45	31.59±1.22	+14.4	NS	NS	NS	26.76±1.19	27.65±0.86	-3.3	NS	*	NS
	2	28.85±1.53	28.86±1.20	+0.0	NS			23.22±1.23	25.10±1.18	+8.1	NS		
Theta (θ)	1	0.91±0.01	0.84±0.01	-7.7	***	NS	0.06	0.88±0.01	0.84±0.01	-4.5	*	NS	NS
	2	0.90±0.01	0.88±0.02	-2.2	NS			0.92±0.02	0.84±0.02	-8.7	*		
R_d $(\mu mol/m^2/s)$	1	-2.54±0.10	-1.93±0.07	+24.0	***	**	0.08	-2.15±0.09	-1.78±0.10	+17.2	*	*	NS
	2	-2.10±0.12	-1.90±0.20	+9.5	NS			-1.90±0.15	-1.55±0.09	+18.4	0.05		
Phi (Φ)	1	0.08±0.00	0.08±0.00	0	NS	*	NS	0.07±0.00	0.07±0.00	-12.5	NS	NS	NS
	2	0.09±0.00	0.08±0.00	-11.1	0.06			0.07±0.00	0.07±0.00	0	NS		
Photosynthesis at mean growth light - Canopy PAR between 9 am to 3 pm and modelled photosynthetic rate at canopy PAR (Amodel)													
Canopy PAR $(\mu mol/m^2/s)$	1	589.4 ± 2.2	453.1 ± 1.6	-23	***	***	***	589.4 ± 2.2	453.1 ± 1.6	-23	***	***	***
	2	471.6 ± 1.9	364.7 ± 1.3	-22	***			471.6 ± 1.9	364.7 ± 1.3	-22	***		
Amodel $(\mu mol/m^2/s)$	1	17.3 ± 0.2	14.9 ± 0.1	-13.8	***	***	NS	16.9 ± 0.2	14.4 ± 0.1	-14.7	***	***	NS
	2	15.2 ± 0.2	12.5 ± 0.1	-17.7	***			14.1 ± 0.2	12.1 ± 0.1	-7.5	***		

Appendix 3: Lettuce trial results

Smart Glass decreased photosynthetically active radiation (PAR) more in experiment 1 relative to 2 and 3:

Average PAR measured using five PAR sensors at the canopy level showed variation in SG light transmission depending on the light intensity. Mean light intensity was higher in experiment 1 (~800 µmolm^{-2}s^{-1}) relative to experiment 2 and 3 (~400 µmolm^{-2}s^{-1}). SG reduced PAR more in experiment 1 (-19%, Dec 2020) relative to experiment 2 (-18%, March 2021) and 3 (-15%, April 2021) (Figure 1). Seasonal variation in light coupled with differential transmission under SG depending on the light intensity created distinct light environments during experiment-1, 2 and 3.

Smart Glass decreased yield in experiment 1 and 2 but not in 3:

Overall lettuce yield determined using plant fresh weight was significantly high in experiment 1 conducted during high light conditions of summer relative to experiment 2 and 3 during low light conditions of Autumn. Interestingly, SG decreased yield of cultivars Butterhead (-11%) and Green Cos (-10 to -15%) in first two experiments only. Lettuce cultivar Red Cos performed poorly and did not respond to the SG (Figure 2).

SG significantly altered leaf color in all three-lettuce cultivars:

Lightness parameter (L*) measured by colorimeter varied with time and was significantly affected by SG. All cultivars showed highest lightness values at the end of third week and plants under SG showed significantly higher lightness values relative to control. Chroma value calculated using a* associated with red (+) and green (-) colour and b* associated with yellow (+) and blue (-) colour showed significant changes in response to SG and the differences were highest towards the end of growth period (Figure 4).

Photosynthetic parameter response to SG:

Lettuce cultivars GC and RC had higher photosynthetic rates than BH. Interestingly, SG significantly reduced (-11%) light saturated CO_2 assimilation rates (A_{sat}) in cultivar Green Cos (GC) but not in Butterhead (BH) and Red Cos (RC). However, SG did not affect stomatal conductance (g_s) in any of the lettuce cultivars (Figure 5).

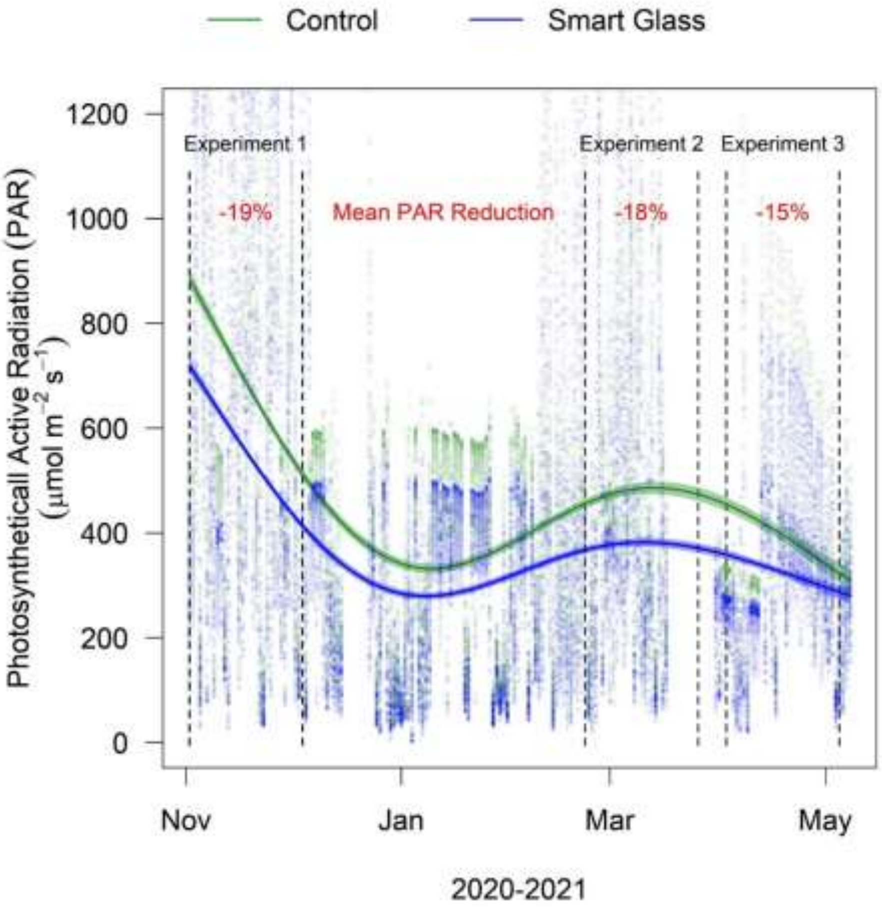

Figure 1. Smart Glass (SG) reduced canopy level photosynthetically active radiation (PAR) more in experiment 1 than experiment 2 and 3. Smooth plot of PAR over time measured during experiment-1 (December 2020), 2 (March 2021), and 3 (April 2021). Points indicate average PAR measured using five PAR sensors at canopy level. Control and SG treatments are depicted in green and blue, respectively. Light green and blue shades along mean lines indicate 95 % confidence intervals.

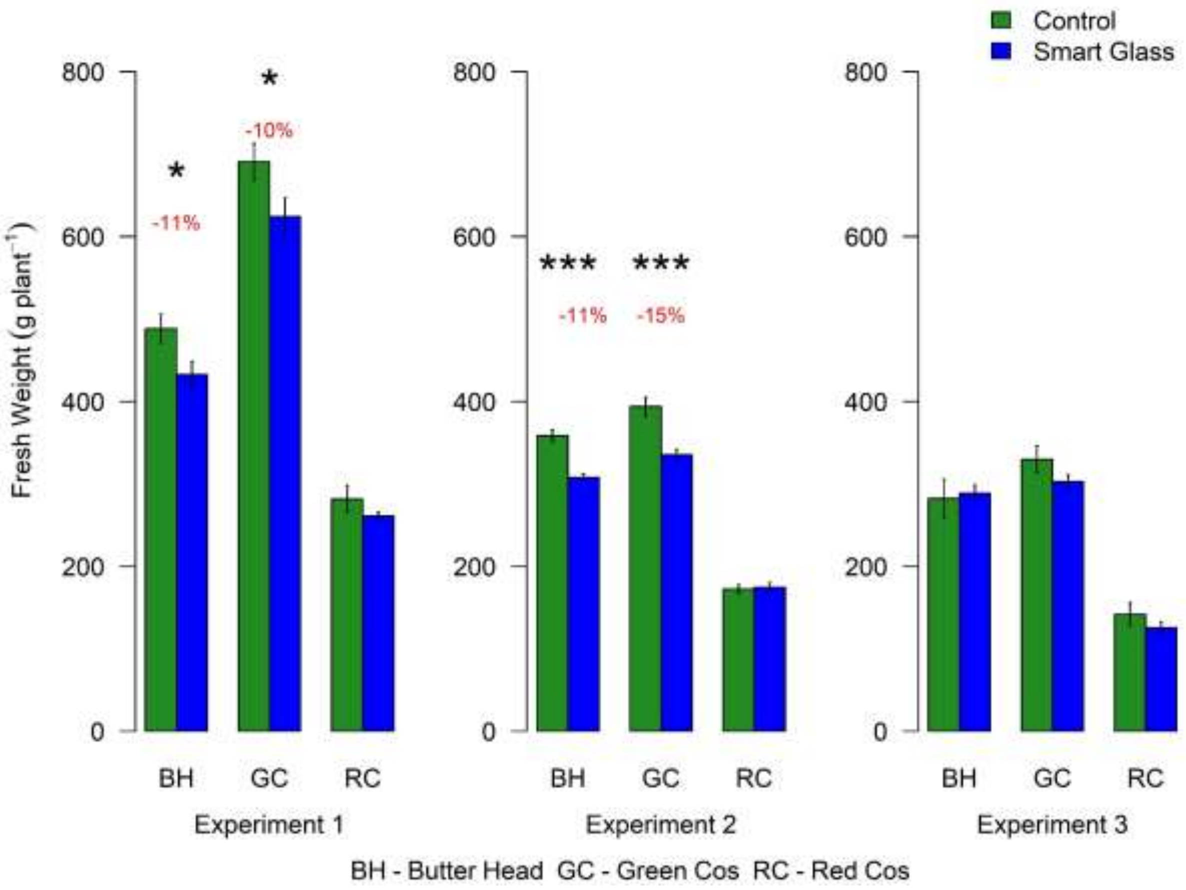

Figure 2. Smart Glass (SG) reduced yield more in experiment 1 than experiment 2 and 3. Bar plot of mean plant fresh weight for cultivars Butterhead (BH), Green Cos (GC), and Red Cos (RC) measured during experiment-1 (December 2020), 2 (March 2021), and 3 (April 2021). Error bars indicate standard error of mean. Control and SG treatments are depicted in blue and red, respectively. Statistical significance levels (*t*-test) for SG effect are shown: **P*<0.05; ***P*<0.01: ****P*<0.001.

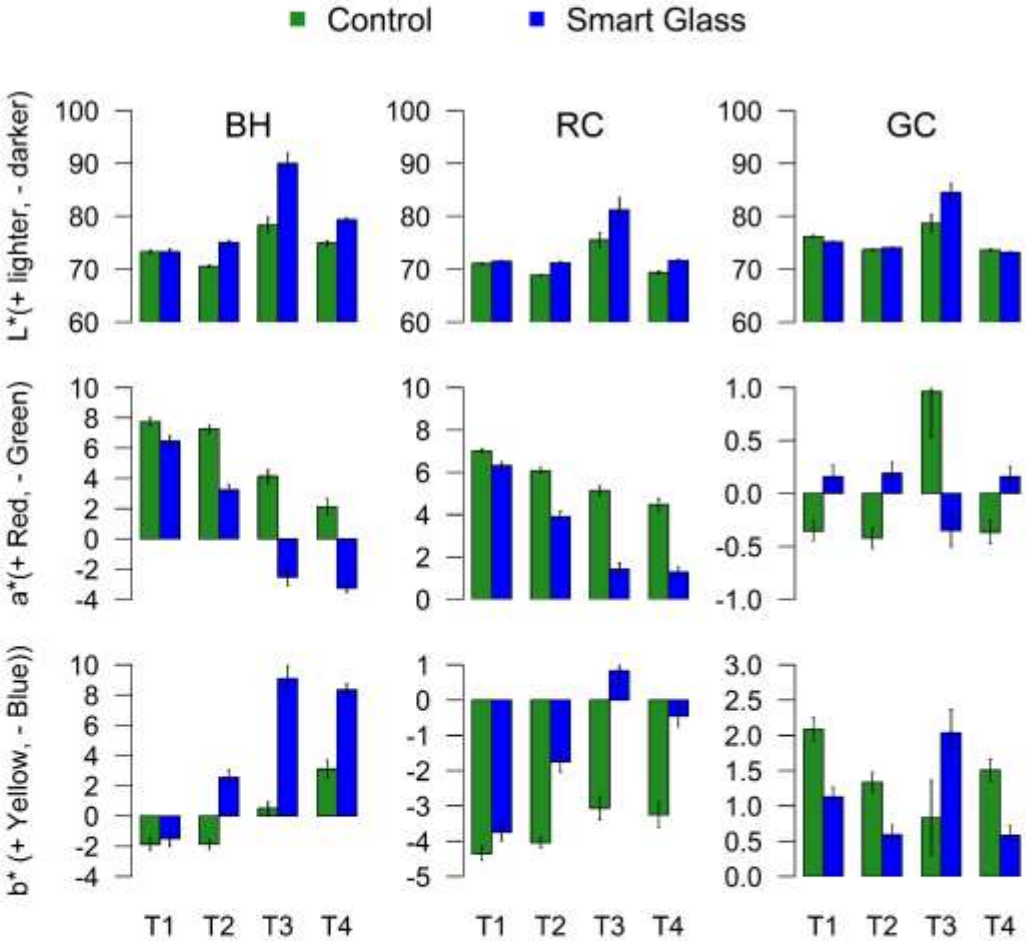

Figure 3. Smart Glass (SG) affected color parameters L*(lightness), a*(+red, -green) and b*(+yellow, -blue) in experiment 1. Bar plot of mean L*, a* and b* for cultivars Butterhead (BH), Green Cos (GC), and Red Cos (RC) at four time points measured during experiment-1 (December 2020). Error bars indicate standard error of mean. Control and SG treatments are depicted in blue and red, respectively.

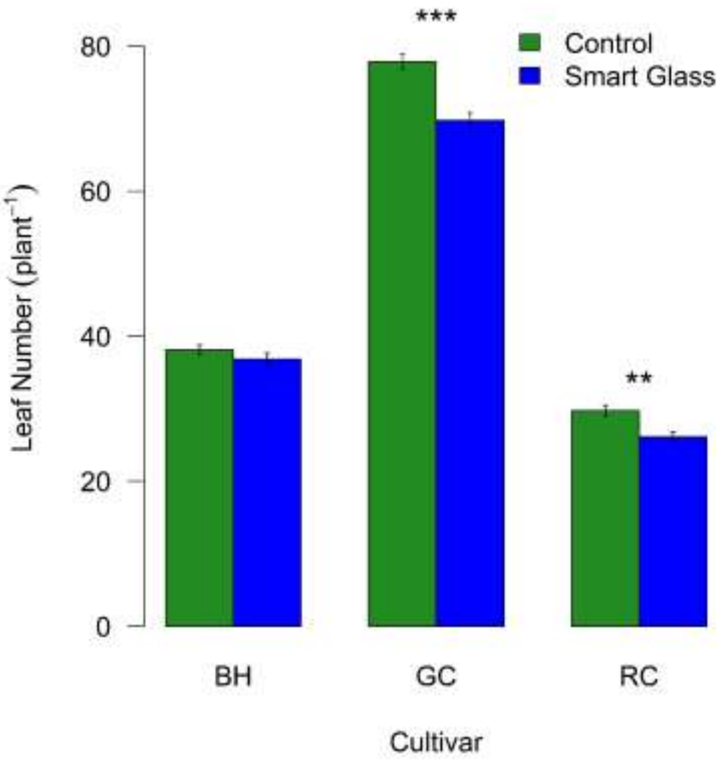

Figure 4. Smart Glass (SG) significantly reduced leaf number in cultivars Green Cos (GC) and Red Cos (RC). Bar plot of mean leaf number per plant for cultivars Butterhead (BH), Green Cos (GC), and Red Cos (RC) at four time points measured during experiment-1 (December 2020). Error bars indicate standard error of mean. Control and SG treatments are depicted in blue and red, respectively. Statistical significance levels (*t*-test) for SG effect are shown: *$P<0.05$; **$P<0.01$: ***$P<0.001$.

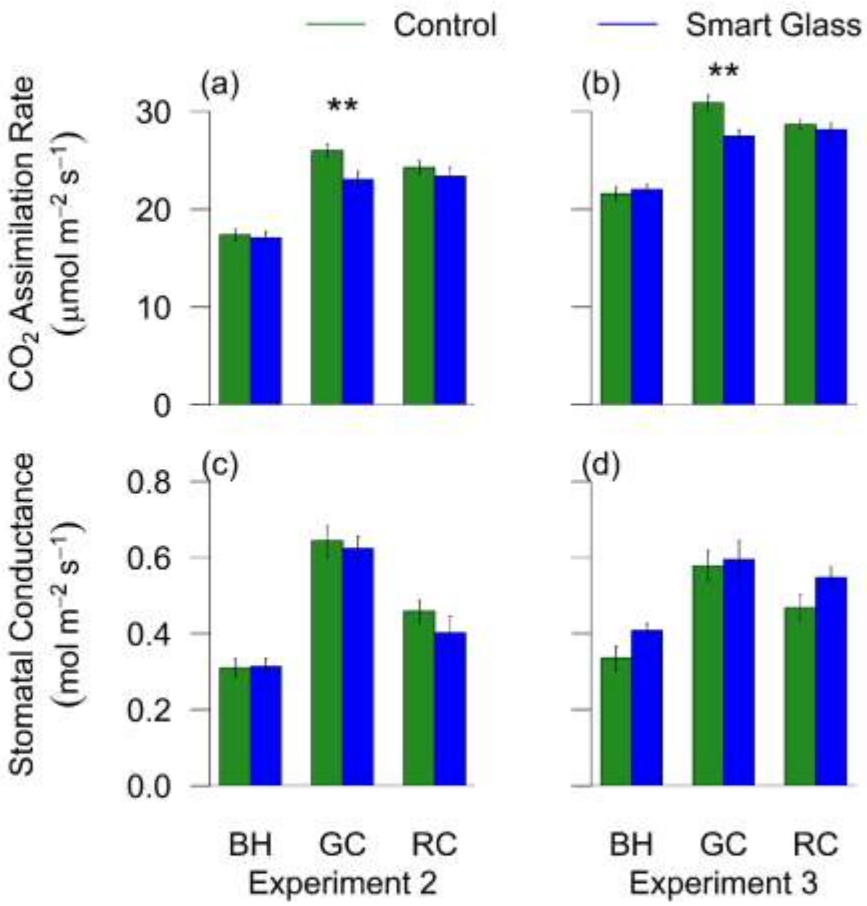

Figure 5. Smart Glass (SG) significantly reduced light saturated CO_2 assimilation rates (A_{sat}) only in cultivar Green Cos (GC). Bar plot of mean A_{sat} and stomatal conductance (g_s) for cultivars Butterhead (BH), Green Cos (GC), and Red Cos (RC) measured during experiment-2 (March 2021) and 3 (April 2021). Error bars indicate standard error of mean. Control and SG treatments are depicted in blue and red, respectively. Statistical significance levels (*t*-test) for SG effect are shown: **P*<0.05; ***P*<0.01: ****P*<0.001.

Appendix 4: SG project engagements

July 2019 - December 2019

Educating next generation on hi-tech protected cropping:

This session included visits from STEAM Visit with Windsor College South. VR footage of facility was recorded, Fast Forward Year 10 Visit (100 year 10 students), Other School visits included- Dundas Public School visit, James Ruse Agri. High School students (80 students), Minto High School Visit (12 students), Hobartville High School Visit (10 students), Kings School (40 year 11 students), Hurlston High School (~30 students), Rural Aboriginal and Torres Strait Islanders student camp (23 people)

Masterclass -was held for 50 High school students, Primary Industries vocational education and training (VET), SuniTafe of Victoria. We also hosted the PCA Masterclass for students (approx. 15).

International collaboration and student visits: Agent Familiarisation Tour for students (50 students), Genesis Horticultural Solutions program with students from India.

Field days with Protected cropping industry-

Regular industry interactions with visitors from DPI, Syngenta, Flavorite, MCA (just to name a couple).

Representatives from Arugga AI Farming and SparkLabs Cultiv8 visited and discussed potential research projects, Interaction session with Achmea Greenhouse Insurance, Field Day with Amateur Beekeeper Association Visit (30 people).

Media coverage on NVPCC experiments:

NVPCC has been featured in the Hydroponic Farmers Federation Newsletter. The program highlighted the facility and potential training/workshops available to the industry.

NVPCC was also featured on Turkeys' Bloomberg channel. Turkish Ag journalists toured facility and produced a short article and recorded interviews for news story.

NAB Bank scheduled a film commercial using the greenhouse.

Photoshoot and article were written by Lisa Truong from Nature Research.

HSBC visited to discuss potential partnership with the university.

January 2020 - June 2020

- Due to COVID – 19, we did not have any engagement throughout the month of April - July.

  July 2020 - December 2020

- Due to COVID – 19, we did not have many engagements throughout the month of April - August.

Facility visits and interaction sessions:

- Lynch Group representatives visited the facility to discuss potential research collaboration.
- Short course on novel technologies and post-harvest strategies in NVPCC for 13 students and 3 observers from Woolworths was held on the 17th of September.
- Alex Soeriyadi of LLEAF visited with 4 media students on the 30th of October.
- Robert Mullin from Syngenta visited to discuss lettuce crop and Smartglass project.
- Interactive session with representatives from Landcom on 16th October.

January 2021 – Present

Educating next generation on hi-tech protected cropping:

- Kris Beazley, Principal of the Centre of Excellence in Agricultural Education -Richmond Agricultural College program with 5 students from Bomaderry Highschool to on February 19th.
- Research interactive session with 48 students from Kings School along with staff from Quantal Biosciences and Catholic Education Diocese of Parramatta

Facility visits, interaction sessions and media coverage:

- Freelance reporter Alexandra Morris and freelance photographer Zoe Lonegran visited to write article about the NVPCC.
- 37 representatives from Commonwealth Bank Specialised Agribusiness Solutions visit glasshouse.
- Alexandra Morris (freelance writer) and Zoe Lonergan (freelance photographer) visited again to interview Dr Michelle Mak and Dr Sunil Panchal for future article.
- Marcus Van Heijst from Priva visited to discuss the integration of 2 new Priva functions: Workload monitoring and data storage on the cloud for easier access.
- Meetings with Vegepod.
- Discussion meeting with LLEAF and vanilla production growers.

Appendix 5: SG project articles (pdf separately attached).

Appendix 6: Talk on “Protected Cropping: Use of Smart Glass to reduce energy cost in future climates”.